May 1996

Ecosystem Diagnosis and Treatment (EDT)
Applied Ecosystem Analysis - A Primer

DOE/BP-33243-2

This report was funded by the Bonneville Power Administration (BPA), U.S. Department of Energy, as part of BPA's program to protect, mitigate, and enhance fish and wildlife affected by the development and operation of hydroelectric facilities on the Columbia River and its tributaries. The views of this report are the author's and do r necessarily represent the views of BPA.

This document should be cited as follows:

Lestelle, Lawrence C., Lars E. Mobrand, James A. Lichatowich Mobrand Biometrics Inc., Thomas S. Vogel -BPA, 1996, Ecosystem Diagnosis & Treatment (EDT) Applied Ecosystem Analysis - A Primer, Report to Bonneville Power Admin. Project No. 199404600, Contract No. 1994AM33243, 112 electronic pages (BPA Report DOE/BP-33243-2)

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ECOSYSTEM DIAGNOSIS AND TREATMENT (EDT)

Applied Ecosystem Analysis - A Primer

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Project Number 9404600
Contract #94 AM 33243

May 1996

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Preface

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ABOUT THIS PRIMER

"There is no saying where the Northwest salmon story will eventually conclude, but it is certain tbat man and salmon will be linked, for as the Indians said from the start: the fate of one mirrors the fate of the other."
-- Bruce Brown, ***Mountain** in **the Clouds***

CHAPTERS

The aim of this document is to inform and instruct the reader about an approach to ecosystem management that is based upon salmon as an indicator species. It is intended to provide natural resource management professionals with the background information needed to answer questions about why and how to apply the approach. The methods and tools we describe are continually updated and refined, so this primer should be treated as a first iteration of a sequentially revised manual

The approach introduced in this primer is currently being applied in the Grande Ronde Basin in northeastern Oregon (Mobrand et al. 1995) and in the Hood Canal region in western Washington. Declining salmon populations in these areas have raised questions about the long term future of these ecosystems--what are the causes of the salmon's decline and what does it portend. Through the application of this approach a better understanding is gained about the factors affecting the salmon. This is an important first step in the formulation of strategies for managing watersheds where salmon is an indicator of biological integrity.

This primer is about a method for understanding ecosystems and the future of salmon within those ecosystems. It is also about a method that recognizes that people and their values and economies are integral parts of the ecosystem. So, for example when we use the term restoration we don't mean it literally-a return to pristine conditions is in most cases both undesirable and impossible. However it is clear that a better framework for understanding and managing watersheds is needed to assure a future consistent with community goals and values. We believe that the method described in this primer could be a step in this direction.

This work is an extension of concepts and ideas first presented in a report dealing with a framework for salmon supplementation in the Columbia River (RASP 1992). These ideas were subsequently broadened and advanced further under the name of the

Ecosystem Diagnosis and Treatment (EDT) method (Lichatowich et al. 1995; Lchatowich and Mobrand 1995; and Mobrand et aL 1995). We have been encouraged by the results of this method in the Grande Ronde Basin and in Hood Canal, and this primer is both a recommendation to expand its use and an effort to make that easier.

In this primer we attempt to cover most aspects of the approach-some in more detail than others. We have tried to keep the presenmtion as simple and free from mathematical formulas and jargon as possible, although some formulas are necessary for completeness. The document is organized into four chapters. Chapter 1 is an introduction and overview of the method, chapters two, three and four describe the main components of the method-the tasks, the theory, and the tools.

Chapter 1

ABOUT EDT

–An overview of the Ecosystem Diagnosis and Treatment Method

"An understanding of the part conditions of streams and tbe processes tbat have changed salmon habitat is critcal to the diagnosis and treatment of depleted salmon populations."

--from *An Approach to the Diagnosis and Treatment of Depleted Pacific Salmon Populations in Pacific Northwest Watersheds.*

The condition of natural salmon populations is a focal point for many activities tied to land and water resources in the Pacific Northwest. The steady depletion of natural salmon runs has stirred concerns across a wide cross section of the region's populace. The salmon have direct economic and cultural value to the region, but their decline also raises questions about the future of *our* natural resources and our environment in general. Our challenge is to set achievable environmental goals and find ways to meet them. Since a premise of the approach presented in this report is that salmon can serve as an indicator of the conditions of a watershed and of its ability to deliver and sustain a range of values to society, it becomes our mission to understand the ecosystem "through the eyes of the salmon."

The dramatic decline of salmon in this region over the past 150 years corresponds with a rapid restructuring of ecosystems-from old growth forests to tree farms, from wetlands to freeways and shopping centers, from wild rivers to regulated rivers, from open ranges to irrigated fields, from wild fish to cultured fish. Today's salmon are faced with far different conditions for survival than those of yesterday. Every aspect of salmon life history is now somehow affected by human activities. Fishing, for example, which was historically located primarily in the lower reaches of main rivers can now extend along the entire routes traveled by salmon in the ocean and rivers.

To the extent that the purpose of natural resource management has been to sustain economic and cultural benefits derived from salmon, it has failed. The trend in abundance and distribution of salmon over the past 150 years shows a clear and steady decline (Netboy 1973; Brown 1982; Nehlsen et al. 1991).

The question is: Do we know how to manage natural resources, especially those with complex life histories like salmon, in a sustainable fashion?

The National Commission on the Environment, in a report issued in 1993 (NCE 1993), concluded:

> *"Inadequate scientific knowledge handicaps almost every aspect of efforts to achieve sustainable development Too little is known to identify confidently either the significant threats to sustainability or their solutions. "*

Kai Lee, similarly concluded (Lee 1993):

> *Today, humans do not know bow to achieve an environmentally sustainable economy.... Human action affects the natural world in ways we do not sense, expect, or control. Learning bow to do all thee lies at the center of a sustainable economy."*

This growing awareness of our inability to manage resources in a sustainable manner is prompting a change in approach throughout the Northwest. Single species management and reliance on technology fixes are gradually giving way to holistic ecosystem approaches (FEMAT 1993; WFPB 1994; Lichatowich et al. *1995).*

This emerging new theme in resource management demands a new, better understanding of the dynamics of ecosystems and how human actions affect them. We must achieve this by learning through the application of a science-based method of management (Walters 1986; Ludwig et al. 1993).

The EDT Method

The approach we are about to describe is referred to as the Ecosystem Diagnosis and Treatment (EDT) method (Lichatowich et al. 1995). It was devised to help diagnose the condition of resources like salmon and the environments upon which they depend. A diagnosis guides the development of rational actions and strategies. Actions may involve land use practices, water management, or habitat restoration.

The EDT method was developed with strong emphasis on the importance of a science-based approach. Fundamental to the scientific method is the use of an explicit conceptual framework within which information about the natural system is gathered, analyzed and organized. A logical linkage between actions and events within the watershed and their effect on values and objectives must be presumed and explicitly addressed. This process promotes learning and provides accountability.

While the ideas we present are based on concepts that are familiar, we believe the EDT method provides a new and useful way of thinking about resources like salmon and their ecosystems.

The Ecosystem Diagnosis and Treatment (EDT) method is a science-based approach to formulating and analyzing actions to maintain or improve the sustainability and production of natural resources. Its chief aim is to provide a theory, a set of tasks, and a collection of tools which can form the basis for technical input in watershed management processes.

The approach provides an ecosystem perspective to natural resource management. The analysis focuses on one or more species, whose dependence on the ecosystem is extensive both in space and time. The approach has been developed and tested using the life histories of migratory salmonids. Their broad migratory range and sensitivity to human activities make them well suited as indicators or diagnostic species. Species other than salmon could be analyzed using the same approach.

Five Premises

The EDT method is formulated around five premises that support the concept of **watershed management:** 1) Management actions, whether aimed at biotic (e.g., fish populations) or abiotic (e.g., water and land) elements, should be built on an ecosystem-directed strategy; 2) A primary goal for management is to ensure the sustainability of renewable natural resources and, where possible, to allow their sustainable use; 3) Certain species or populations that are dependent on the relative stability of ecological processes over a wide expanse of the watershed can serve to help diagnose conditions for sustainability; 4) Use of the scientific method in management will increase understanding of important ecological relationships; and 5) Information generated through using the EDT method will be of most benefit if it is incorporated into an on-going and iterative management process.

It is an Ecosystem Strategy

Watershed management actions should be built on, or be consistent with ecosystem-directed strategies that promote or maintain ecologically healthy watersheds. It is useful to consider actions as either tactics or strategies. Tactics address local, immediate, or short-term needs-strateges address comprehensive and broad concerns often having a longer time horizon. Management actions are more likely to succeed if they are directed by, and consistent with, an overall strategy based on sound scientific principles. Management actions have too often been the result of tactical-level planning without the benefit of clearly formulated watershed strategies (Doppelt et al. 1993).

A management strategy based upon an ecosystem perspective provides a scientific basis for evaluating, coordinating, and prioritizing watershed actions in a consistent manner. An ecosystem strategy is holistic; it recognizes that biotic and abiodc components of a watershed are interconnected. Hence it must consider the long term and collective consequences of many activities throughout a watershed. Moreover, an ecosystem strategy needs to incorporate human economies and values as well, because people cannot be separated from nature (Grumbine 1994).

An ecologically healthy watershed may be defined as one with "the capability of supporting and maintaining a balanced, integrated, adaptive biological system having the full range of elements and processes expected in natural habitat of the region" (Angermeier and Karr 1993). This definition of ecological health underscores the importance of planning that considers the entire biotic community and emphasizes sustainability.

We Seek Sustainability

A primary management goal is to ensure the sustainability of valued renewable natural resources. The most important challenge facing environmental management is to foster a balance between short term human needs and ecosystem sustainability (Ruckelshaus 1989; Lee et al. 1992).

Sustainability is defined as the process of change in which the continued exploitation or protection of resources, the direction of investment in land and water, and associated institutional changes are consistent with future as well as present objectives for perpetuating environmental qualities and socioeconomic functions of ecosystems (WCED 1987). Human communities generally desire that resource-based values and objectives associated with the water and land of a watershed be sustainable, even within the context of watersheds that have undergone major changes to accommodate human needs. The concept of sustainability must also recognize that ecosystems are constantly evolving. The management concern we raise when we worry about sustainability is the direction and rate of this evolution. All valued natural resources may not be concurrently sustainable in all watersheds.

We Use the Concept of Diagnostic Species

Certain species or populations that are dependent on the relative stability of ecological processes over a large portion of a watershed can be used to help diagnose conditions for sustainability. The shift toward ecosystem management that has occurred in recent years is a move away from a conventional single species approach to a whole system, multi-species framework (Grumbine 1994). This shift poses a problem: How do we assess the condition of ecosystems, given their inherent complexity? The use of appropriately selected indicator or diagnostic species provides a way of coping with this complexity. (Soulé 1987; Karr 1992; Lee 1993).

Instead of trying to understand all dimensions of an ecological whole, the use of indicator organisms that are sensitive to an important cross-section of those dimensions gives needed focus for an assessment (Lee 1993). Implicit in this concept is the assumption that a species which is sensitive to a wide variety of ecosystem conditions is useful as a pulse on the system.

Desired conditions for the entire ecosystem may be achieved through actions guided by the needs of populations that fill representative (umbrella species) or key (keystone species) functional roles within the ecosystem (Walker 1995). This approach may be the most effective way currently available to achieve ecosystem sustainability (Olver et al. 1995; Walker 1995). The EDT method uses the term “diagnostic species’ to emphasize that it is a device to aid in diagnosing and treating watershed conditions.

Migratory salmonid species, like salmon, are highly suited to serve as diagnostic species. Their freshwater life history depends upon streams, the arterial system of the watershed. Streams are generally regarded as a good reflection of overall watershed condition, since water drains downhill, bringing with it characteristics created by conditions upstream. Salmonids are sensitive to these characteristics (Bjornn and Reiser 1991). Because fish are often primary determinants of ecosystem structure (Brooks and Dodson 1965; McQueen et al. 1986), conditions shaping their survivability and life history are important to ecosystem structure.

Certain salmonid species (e.g. spring chinook, coho, and steelhead) utilize extensive portions of the watershed, from the mouth of the river to the headwaters of many of its connected branches. To complete their life cycles, individuals of these species experience the condition of the river from the spawning grounds, often located high in the watershed, to the estuary. Hence the completion of their life cycle depends upon the connectivity of the stream network over various life stages (Lichatowich and Mobrand 1995). These life stages, which can number seven or more (e.g., prespawning, spawning, incubation, colonization, summer rearing, overwintering, and smolt migration) have different habitat requirements (Bjornn and Reiser 1991); therefore sustainable life history patterns require the existence of diverse habitats.

Migratory salmonids have another important, unique role-they connect ecosystems through their extensive migrations. For example, spring chinook spawned in the upper Grande Ronde River in Northeast Oregon utilize not just this river, but the Snake and Columbia Rivers before moving into the Pacific Ocean. There, they travel extensively for several years prior to their return journey to natal streams. The concept of ecosystem management ultimately must recognize that watersheds (or ecosystems) are not isolated (Maser and Sedell 1994); conditions in one can have profound implications for the sustainability of resources in another. Moreover, salmon are among the few species that cycle nutrients between all these environments (Kline et al. 1993; Bilby et al. 1995; Willson and Halupka 1995).

The potential magnitude of nutrient cycling by salmon and its role in ecosystem function have long been acknowledged (Juday et al. 1932; Donaldson 1967); but, in general, their importance has received scant attention by scientists (Willson and Halupka 1995). Recent findings suggest that nutrient cycling may be very important to the structure and stability of some watersheds, supporting the conclusion that salmon should be considered a keystone species in these systems (Bilby et al. 1995). A keystone species is one that plays a critical role in maintaining the biological integrity of the ecosystem to which it and many other species belong, the loss of such species leads to cascading changes in ecosystem structure (Paine 1969; Paine 1995).

This potential keystone role is seen in the importance that anadromous salmonids have had historically, and continue to have in many areas, as critical nutrient sources to numerous species (Willson and Halupka 1995). The enormous influx of biomass to freshwater systems that can occur through anadromous adult salmonids and their progeny can be heavily exploited by mammal, bird, and fish species, affecting the distribution, survival, and reproduction of these non-salmon species.

The findings by Bilby et al. (1995), and their on-going work, provide evidence that the capacity of salmon streams to support fish may be progressively declining due to reductions in nutrient loading caused by diminishing numbers of spawning salmon.

In addition to serving as indicators of the quality of watersheds, salmon species symbolize the vitality of the Pacific Northwest to human communities (Jay and Matsen 1994). Salmon are integral to the heritage and present-day values of people throughout the region. In a sense, they are an icon of the quality of life in this area.

We Employ the Scientific Method

Application of the scientific method helps improve understanding of the effects of human actions on ecological conditions and relationships over time. If natural resources are to be managed in a sustainable manner, then actions need to be guided through a process that incorporates scientific learning.

Fundamental to the scientific method is the statement of a theory-an explicit conceptual framework-within which we can understand and explain our observations. A framework helps us prioritize, organize and analyze information about the natural system. It is a vehicle for conceptualizing how actions are transferred through the ecosystem to ultimately affect values and objectives that define the purposes of management. A framework is necessary to the formulation of hypotheses and to the design of monitoring and evaluation programs to test them. When new observations conflict with framework assumptions, we revise the elements of the framework, and thus promote progressive learning.

An explicit conceptual framework also helps ensure the accountability of the learning process. We can determine if indeed hypotheses about the effect of actions on outcomes are consistent with the framework. Hypotheses and assumptions that are critical to the effectiveness of actions can be identified and tested. The scientific framework (or theory) is the basis for our ability to provide useful and credible information to decision makers.

We Assume Information Responsive Decision Making

Watershed management should be driven by a decision process that is based upon learning by doing, often referred to as adaptive management (Walters 1986; Lee 1993). This approach to decision making allows action in the face of scientific uncertainty. It serves two important functions: it provides assurance that watershed management is progressive- those actions that are effective are continued and those proven ineffective or damaging are discontinued; and it also provides the means for an open decision making process where the public has the opportunity to remain informed and participate effectively. Both scientific information and stakeholder values must be effectively incorporated into the decision process.

Components of the EDT Method

In Chapters 2, 3, and 4 we describe the ***Tasks, Theory, and Tools*** that comprise the components of the EDT method (Fig. 1.1). The three components complement each other. The ***Tasks*** set forth a specific sequence of actions; they explain what needs to be done and in which order. The Theory is the conceptual framework needed to apply the scientific method, and the Tools are methods, procedures and aids designed for analysis and communication. Each component is described briefly below.

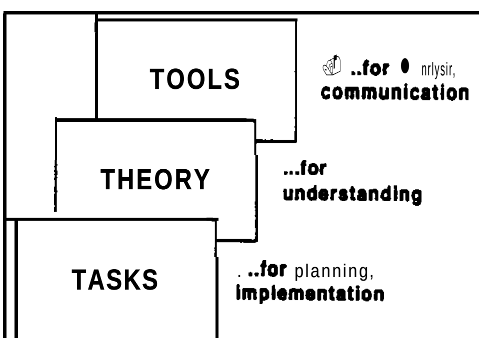

Figure 1.1. Components of the EDT method

The Tasks are composed of a sequence of planning and implementation steps introduced in Lichatowich et al. (1995). The sequence forms an iterative cycle of planning, implementing, and learning 1) Identification of objectives; 2) Diagnosis; 3) Formulation of strategies and actions;

4) Trade-off analysis; 5) Revision of objectives; and 6) Prioritization and sequencing and implementation of actions, including monitoring and evaluation. Several of these steps require policy direction-we confine our discussion to the technical elements of the process.

The Theory is the conceptual framework that give the tasks purpose and meaning. Watershed management has a logical requirement-we must be able to see the whole and its parts in a consistent way. This requires conceptualizing the system in a manner that is useful and consistent with ecological theory. We call this conceptualization a framework or a theory. The architecture of the framework is prevailing ecological theory, and its building blocks are the assumptions which explain our observations and rationalize our actions. The EDT method incorporates an explicit conceptual framework for understanding how actions will affect the ecosystem.

The Tools are analytical procedures or conceptual devices used in performing analyses. Four categories of tools are described: 1) diagnostic procedures and models; 2) procedures for strategy development; 3) procedures for trade-off analysis; and 4) monitoring and evaluation procedures. These tools include procedures for capturing data (a database system), for analyzing information (models and analytical routines), for displaying results (graphics and reports), and for prioritizing monitoring and evaluation.

Regarding Terminology

The terms “watershed” and “ecosystem” are sometimes used interchangeably. In this paper we use the term watershed to mean the geographic area defined by a drainage or catchment basin. Its boundaries are the ridge tops that separate it from other watersheds. But, the range of a salmon extends beyond the watershed (e.g., it includes portions of the ocean)—we sometimes refer to this range as the “extended watershed” for a certain salmon population. The concept of an ecosystem on the other hand incorporates biological function and interrelationship among species, populations and environment within a functional unit.

Ecosystems like watersheds are hierarchical in structure. We also occasionally use the term “healthy” with reference to an ecosystem. By a healthy ecosystem we mean a condition where desired values and products can be provided on a sustainable basis. We usually assume that a pristine ecosystem is healthy, however agriculture and urban ecosystems may also be healthy by our definition. For a more in depth discussion on this subject, see Costanza et al. (1992).

Chapter 2

ABOUT TASKS

-An Implementation Strategy

"In preparing for battle I have always found that plans are useless, but planning is indispensable."

-- Dwight D. Eisenhower

Planning is fundamental to watershed management. Planning that supports adaptive management needs to be recursive (Kershner et al. 1991; Lchatowich et al. 1995). It involves the deliberate, repeated process of identifying what we know, what we think we know, and what we don't know. The fruits of such planning are rational actions that are consistent with our knowledge. It provides for accountability and progressive learning.

The adaptive approach to management recognizes that the information we base our decisions on is almost always incomplete. The approach treats actions as experiments with the imperative that we learn from them (Walters 1986; Lee 1993). The adaptive approach is not random trial and error learning. Nor is it a device to side-step uncertainty and proceed with ill-conceived actions. Instead, it is designed from the outset to test clearly formulated hypotheses about the behavior of the ecological systems being changed by human use (Lee 1993). It is a thoughtful and disciplined application of the scientific method.

The EDT method was developed to be used within the context of adaptive management. The method employs a sequence of planning and implementation steps (Lichatowich et al. 1995) which are repeated to form an adaptive learning cycle. The planning sequence consists of six categories of tasks (Fig. 2.1). The tasks should be seen as guidelines and not rules. They are meant to stimulate thinking about the structure and function of the ecosystem. Each task is described below.

Task 1 - Identify Objectives

The first step is to identify applicable objectives for watershed management. These objectives may be broadly worded and may address overall watershed conditions,

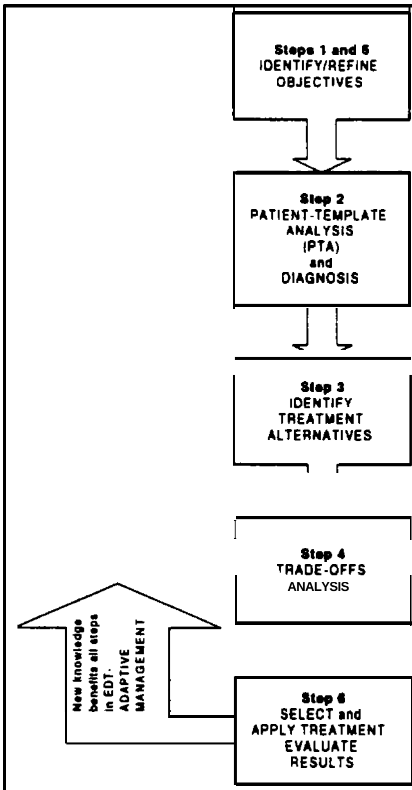

Figure 21. Ecosystem diagnosis and treatment **EDT) planning** process.

but they are often more specific with reference to certain populations, groups of populations, or their habitats. It is important to clearly define the explicit biological and socioeconomic objectives and performance indicators (Stephenson and Lane 1995).

A broad array of human values affect perspectives and decisions regarding a watershed and its natural ecosystem components. A premise of the EDT method is the desire for conditions that lead to sustained achievement of objectives, and these conditions in turn are predicated upon the health and stability of ecosystem processes within the watershed. The expectations regarding the sustainability of valued conditions give direction to planning.

Objectives that can focus and set scope for planning are sometimes found in records from public hearings, opinion polls, agency documents and projects goal statements. Objectives are used to bound and direct the planning process in the succeeding steps.

Analysis of risks and trade-offs associated with action alternatives requires an additional set of broader and more inclusive objectives that reflect all potentially affected values. Thus the result of the first step in the planning process should be both a statement of the vision for the future of the watershed (to focus the search for solutions) and a broad inventory of values and concerns (to set scope for the trade-off analysis).

Task2 - Perform Analysis and Diagnosis

What prevents us from achieving our objectives? The purpose of the diagnosis is to address this question. Just as human patients differ and each diagnosis is unique for an individual, watersheds and their populations differ. Diagnoses are specific to watershed conditions and objectives.

Focus for the diagnosis is provided by the selection of one or more indicator species, or populations. We assume that an appropriately chosen species can be viewed as an indicator of the ability of the watershed to deliver the values and objectives.

The process of transforming objectives into a format organized for analysis begins with the formulation of a conceptual framework that reasonably represents the factors that affect the objective conditions. The framework should be designed to compare existing and desired conditions using terms that are understandable, and the results must be interpretable for use in designing treatment actions.

A generalized approach for comparing existing and desired conditions is called the Patient-Template Analysis (PTA) (Lichatowich et al. 1995). This approach uses medical analogies to compare existing conditions of the diagnostic populations and their habitats (Patient) with hypothetical healthy conditions (Template) to form a diagnosis of the subject's status and thereby arrive at one or more sets of possible treatments.

The Template describes sustainable conditions. Representative, stable systems that can be used as models for comparisons are not easy to find, although they do exist for some applications. Literature regarding other populations in similar watersheds can be very helpful. One approach found to be instructive is to infer the Template by reconstructing a representation of historic conditions of the subject populations, their life histories, and their habitats. Sufficient information normally exists to do this with the level of clarity needed for the analysis.

The Template should not be confused with objectives. Watersheds and their ecosystems evolve constantly; we cannot recapture the past, but we can learn from it. The Template serves to bring an understanding to the range of conditions that can naturally occur in the system of interest within the prevailing climatic, geologic, and geographic setting in which it is located. Use of historical information in this manner has been found to be highly informative (Sedell and Luchessa 1982; Langston 1995).

The Patient describes existing conditions in the same scales of place, season, and life history used to describe the Template. In most cases, there is an abundance of information and data on which to formulate this description.

The diagnosis is performed by comparing the Patient and Template to identify the factors or functions that are preventing the realization of objectives. The diagnosis can be qualitative or quantitative, depending on the type and quality of the information used to describe the Patient and Template. Regardless, the diagnosis forms a clear statement of understanding about the present condition of the watershed as related to the diagnostic species.

The diagnosis then provides a rational way of identifying potential actions that can be taken to address factors affecting specific, defined life history-habitat relationships for the diagnostic populations.

Task 3 - Formulate One or More Strategies and Associated Action (Treatments[1]) Alternatives

This step involves formulating treatment alternatives. The term "treatment" implies that watershed actions should be consistent with maintaining or improving the condition or sustainability of the diagnostic species.

The purpose of this step is to identify a range of reasonable candidate actions. Proposed actions can come from many sources-from individuals, organizations, and agencies. 'The purpose of the treatment identification step, however, is to ensure that among the collection of alternatives are some that are based upon the diagnosis.

The procedure for identifying actions consistent with the diagnosis involves first formulating one or more system-wide strategies. A strategy sets an overall direction to guide the development of watershed actions. Basin-wide strategies should be framed upon principles of watershed dynamics, ecosystem function, and conservation biology. These principles can be simply captured in one general principle using a life history perspective for the diagnostic species. In simplest terms, the principle calls for setting the following strategic priorities: first, maintaining; second, improving, and third, restoring.

These strategic priorities provide a basis for establishing guidelines to identify reasonable and effective actions.

Task 4 - Describe Benefits and Risks (Trade-off Analysis)

Following the identification of candidate -actions, an analysis of trade-offs is performed to compare benefits and risks of individual or suites of actions. All aspects of natural resource management involve uncertainty. Conceptualization of ecological relationships and functions, diagnostic analyses, and selection of treatments incorporate assumptions that create uncertainty. Uncertainty poses risks.

Risk here refers to the possible outcomes of the candidate actions in terms of objectives and stakeholder values. It should be noted that "no action" is also an action, and it too poses risk. The question of risk involves whether actions will move the system closer to achieving objectives (benefits or increased values) or further away from those objectives (reduced values). The nature and extent of these potential consequences and the likelihood of their occurrence need to be considered in analyzing trade-offs.

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[1]/The terms "treatment" and "action" are used interchangeably. A strategy is defined as a suite of actions, or treatments, with a common, or integrated, purpose.

Incorporating risk into the decision process requires two steps: scientific inquiry and social evaluation. The level of risk can be determined through scientific evaluation of the uncertainties and assumptions. However, deciding how much risk to accept is a social evaluation. Social evaluation becomes important when actions to improve ecosystem conditions will incur large economic costs or trade-offs to the community.

Task 5 - Refine Project Objectives

The objectives identified in Task 1 need to be evaluated based on the diagnosis and trade-off analysis. This evaluation should consider the likelihood of achieving specific objectives and the risks and costs of doing so. Evaluation of these factors, and resolution of apparent conflicts among competing values and objectives, can lead to revised objectives or suggestions for specific alternative treatments.

Revised objectives and proposed alternative treatments should be analyzed using methods outlined in Tasks 2 and 4. Completion of this step will produce one, or a set of, alternative treatment(s) designed to achieve the stated objectives, along with statements of likely benefits and risks associated with each alternative treatment.

Task 6 - Treatment Application, Monitoring, and Evaluation

The diagnostic, analytic, and refinement steps may produce several alternative strategies and treatments (or actions), all of which could achieve the desired conditions. It is suggested that the selection of specific strategies and actions for implementation should occur in an open public process. The results of the analysis of benefits and risks associated with both accepted and rejected actions should be made available for public review.

Monitoring and evaluation along with public comment will generally be the sources for amendments to a watershed management program. To facilitate and promote true adaptive management that incorporates updated information, the entire program should be reviewed on a routine schedule. Information or decisions associated with each of the six steps in the process would be reviewed and updated as needed according to that schedule. Treatment results measured during monitoring are analyzed and integrated with other factors to evaluate program progress. This provides for program accountability and leads to design of the next iteration in the planning cycle.

Chapter 3

ABOUT THEORY

– A Conceptual Framework

"The concept of ecosystem management, with or without experimentation, has a logical requirement: that one be able to see the ecosystem as a whole in some fashion."
-- Kai Lee, Conpass and Gyroscope

Theory is essential to understanding and communicating complex natural phenomena. A theory is a set of ideas, concepts, or principles used to explain a wide range of observations. In biology,. for instance, fundamental principles are generally not stated as laws but as frameworks of concepts (Mayr 1982). Such frameworks contain sets of assumptions that explain how complex ecosystems behave.

If adaptive management is to prove useful, it is imperative that the theoretical underpinnings of strategies and actions be made explicit and readily understood. The rationale for actions cannot be evaluated apart from a knowledge of the theoretical basis for those actions. Management programs that proceed without an explicit conceptual framework offer a very erratic and inefficient path toward learning (Lichatowich and Mobrand 1995).

Theory needs to be judged according to three basic questions or criteria: 1) Is it consistent with what we observe; 2) How well does it explain what we observe; and 3) Is it useful for guiding future actions? Adaptive management of ecosystems should incorporate theory that meets these criteria.

The declines in abundance and distribution of organisms like Pacific salmon are seen as evidence that the theoretical basis behind much of the management that has occurred during this century has been faulty and misleading (Nehlsen et al. 1991; Ludwig et al. 1993; Bella 1995; Frissell et al., in press). Bella (1995), for example, states that the problem is that our theoretical frameworks have not enabled us to grasp the severity of cumulative impacts on these resources. He asserts that subtle interactions of many diffused impacts have escaped notice using conventional analytical approaches. Such pervasive misperceptions, he notes, explain the decline of salmon stocks in spite of the scientific effort to protect them.

Similarly, F&sell et al. (in press) conclude that today's salmon crisis is due largely to an overly simplified view of how natural systems function. That view, they suggest, fails to incorporate the many important interactions within the ecosystems, leading to false conclusions about the collective consequences of many actions spread throughout the ecosystem.

It is apparent that new perspectives are needed to formulate useful conceptual frameworks. To understand the relevance of concepts incorporated in the EDT framework, it is helpful to first review other related approaches that have influenced how this framework was developed.

CHAPTERS

About Conceptual Frameworks

Three theoretical approaches that have been used to formulate management actions for watersheds and their populations are reviewed here: limiting factors analysis, watershed analysis, and population dynamics analysis. These all have short comings.

Limiting Factors Analysis

The most widely used approach for assessing the effect of environmental factors on salmon populations involves what is loosely referred to as limiting factors analysis. This approach is based on a concept that considers factors affecting a population as a "bottleneck" to abundance (Fig. 3.1a-b). It is widely cited as a way of conceptualizing the relative importance of factors that regulate the abundance of fish populations (Hall and Field-Dodgson 1981; Nickelson 1986; Hunter 1991; Reeves et al. 1991; Nickelson et al. 1993).

The premise of the limiting factors concept is that the upper limit to population size is determined by the resource in least supply (RickIefs 1973; Begon and Mortimer 1986). If the supply of that resource is increased, the population can theoretically grow until constrained by the next most limiting resource (Fig. 3.1c). Competition for food or space in the most constricting life stage is seen as the "bottleneck" to population size. This view has led to the popular idea among biologists that stream populations are limited in size by one life stage or another, such as by summer habitat or over-wintering habitat (Reeves et al. 1989; Hunter 1991).

This notion of a limitation in one stage or another has been extended by many biologists to cover a broader range of factors affecting population abundance over an animal's life cycle, resulting in an extremely simplified diagnosis of population health. Fish biologists have extended the concept to include, for example, mortality

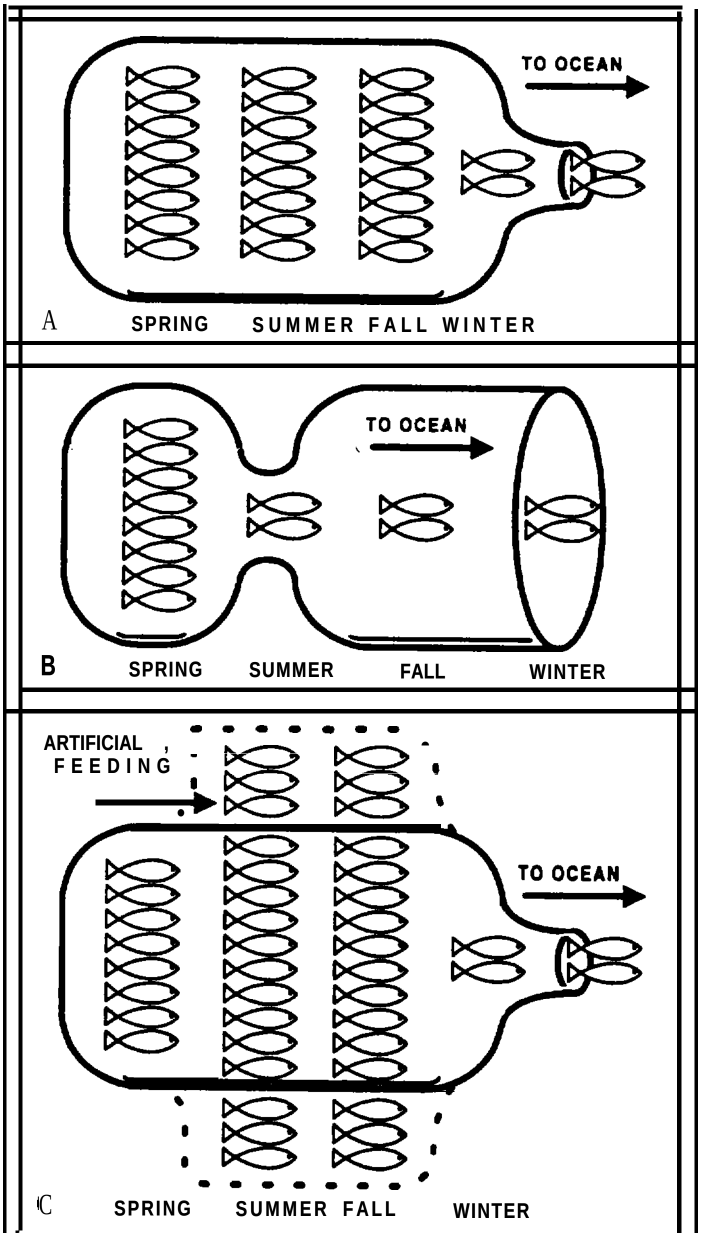


Figure 3.1(a-c). Examples of limiting factors based on the "bottleneck" concept where the limitation occurs (A) during winter before seaward migration of smolts, and (B) during the previo summer. Artificial feeding to increase capacity during summer (could be negated by a bottleneck the following winter. Taken fro Reeves et al. (1991).

from fishing and passage over dams. Hence Huppert and Fight (1991) concluded that "some stocks are habitat-limited while others are limited by fishing mortality." Using similar logic, Reeves et al. (1989) concluded that unless "optimal spawning escapement" is expected within five years that it would be difficult to justify habitat improvement projects.

This concept of limiting factors has resulted in a view held by many that an improvement in the condition of animal populations like salmon first requires that the "most limiting factor" be addressed before improvements in other mortality factors can be beneficial. Thus improvements in habitat condition are seen as being of little or no value if freshwater habitat is "underseeded" by natural spawners (e.g., Reeves et al. 1989; Huppert and Fight 199 1). The solution in that case, by such reasoning, is to increase the number of spawners by reducing fishing or dam passage mortalities that occur downstream.

This narrow view explains why the region has been locked in debate over which of several possible problems is the principal problem with salmon natural production. Such thinking has actually contributed to the current plight of many salmon populations. It has led to attempts to solve ecological problems without seeing, or addressing, how cumulative effects are impacting populations. In other words in order to understand the significance of life stage specific capacities we must analyze their contributions to the cumulative (full life cycle) capacity (Moussali and Hilbom 1986).

Watershed Analysis

Another related diagnostic approach is watershed analysis'--part of two recent initiatives to implement ecosystem management concepts on Washington State and federal lands (WFPB 1994; FEMAT 1993). The approach is aimed at development of a scientifically based understanding of the major ecological processes and their interactions occurring within watersheds.

A principal objective of the approach is to gain understanding about how land use practices affect key species, like salmon. In particular, a better understanding is sought about the cumulative effects of more than one land use activity on these species. The focus of the analysis on Washington State lands is fish habitat. The intended use of the analysis is to help guide management actions.

While watershed analysis is described as a "set of technically rigorous and defensible procedures" (FEMAT 1993, V-55), which includes "limiting factors analysis for key species," it is more accurate to describe it as a set of general guidelines for considering how watershed processes occur. It is primarily aimed at physical environmental processes. No attempt has been made to incorporate a theoretical basis for analyzing how these processes affect populations such as salmon. There is no basis for drawing inferences about cumulative effects.

For watershed analysis to be of practical use in prioritizing actions for populations like salmon, it needs a conceptual bridge to link environmental factors to population biology. Without such a bridge, or framework, resulting analyses are merely descriptive and lack a clear rationale for linking actions and expected outcomes.

Population Dynamics Analysis

The analysis of population dynamics is an old discipline with roots that predate the modem science of ecology. Although interest in its study has ebbed and flowed over time, it has had a major role in shaping ecological theory (Begon and Mortimer 1986) and the management of many animal populations (Caughley 1977; Hilbom and Walters 1992). More recent efforts to integrate ecological concepts into population dynamics theory have been encouraging (Cappaccino 1995). The challenge of these efforts is to make use of species survival relationships derived from population dynamics to understand the structure and function of ecosystems.

The most well known type of analysis of fish population dynamics is called stock-recruitment, or spawner-production (S-P), analysis (Ricker 1954; Hilbom and

[2]/The term "watershed analysis" is being revised within the federal planning process to "ecosystem analysis at the watershed scale" to emphasize its role in moving toward ecosystem management (REO 1995).

Walters 1992). The approach is based on an assumption that there exists some underlying relationship between spawner Abundance (parent stock) and resultant production (progeny). This type of analysis has been mainly applied in harvest management, though its use has been extended to other types of environmental issues for various species (Christensen et al. 1977; Belovsky and Joem 1995; Emlen 1995).

A spawner-production relationship is a simple conceptual model meant to depict how population abundance varies in relation to the size of the reproducing parent population (Fig. 3.2). The result is a curve of variable mortality as a function of population density. Total mortality rate, which consists of two components-density-independent and -dependent mortality-increases with increasing population density due to progressively greater competition for needed resources.

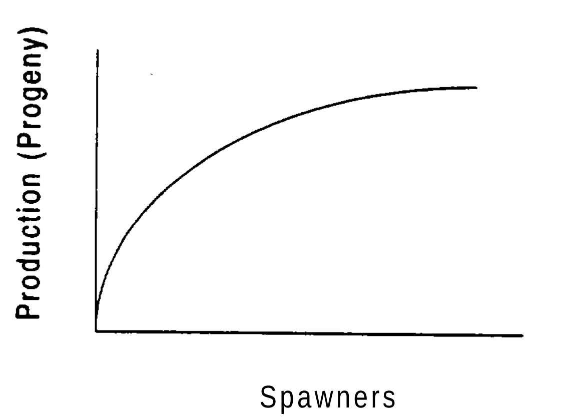


Figure 3.2. Spawner - production relationship.

At extremely low population densities, the rate of mortality on a population is theoretically unaffected by the abundance of that population; hence mortality rate is largely density-independent at these densities. As population density grows, competition for food and space typically increases, thereby increasing mortality beyond the rate imposed solely by density-independent processes. This additional amount of mortality is the densitydependent component of mortality. The population is ultimately constrained to some carrying capacity by limited food or space.

A major criticism of this approach is that it is used to represent aggregates of many populations or subpopulations, each of which may have different production characteristics. This invariably leads to the overharvest of less productive stocks and the gradual decline of the stock aggregate (Larkin 1977). Similarly, the fact that real data rarely exhibit clear relationships between spawners and production also appears to be due in part to overaggregation (DeAngelis 1988). More useful results can be obtained if populations are disaggregated into separate components or life stages (Rothschild 1986; Moussalli and Hilbom 1986; Lestelle et al. 1993b).

EDT Conceptual Framework

The EDT conceptual framework incorporates aspects of those described above. It was developed with an aim toward utility for salmon management but also with the important goal of maintaining consistency with an ecosystem approach. The framework accomplishes this by viewing salmon as an indicator, or diagnostic, species for the ecosystem. The salmon's perspective, its perception of the environment, becomes a view of the system as a whole. Within the limitations of the perspective of the salmon and our ability to interpret it, this approach provides a **framework** for formulating strategies for salmon in the context of watershed management.

The framework was designed to be simple in concept but with sufficient dimensional complexity to accommodate temporal, spatial and biological detail. Conceptual simplicity is important because unless ideas can be communicated clearly and without ambiguity nothing is gained.

The usefulness of this type of framework should be measured by how well it generates insights into ecological patterns and relationships that might otherwise be missed or glossed over (Bunnell 1989; Lee 1993). As a theoretical construct, it is a caricature of nature against which to test and expand human experience (Walters 1986).

Watersheds and ecosystems are by nature hierarchical (0'Neill et al. 1986). Concepts and terms must be consistent at all levels in the hierarchy. Therefore the EDT framework was designed so that analyses made at different scales-from tributary watersheds to successively larger watersheds (e.g., Wallowa River to the Grande Ronde River to the Snake River to the Columbia Basin)-might be related and linked. Ultimately, conditions within these watersheds can be linked to those within the Pacific Ocean.

This feature of the conceptual framework enables consideration of conditions for sustainability that link all components of an extensive and complex life history, such as that exhibited by salmon, over successively larger spatial scales. It is the key to our ability to assess the cumulative effects of concurrent actions spread across the geographic range of salmon.

The Basic Framework

In its simplest form, the conceptual framework is a pathway for linking potential management actions (or natural events) to outcomes that may be relevant to society's values or objectives (Fig. 3.3). It provides a system of logic (rationale) to explain how actions are transferred into desired outcomes.

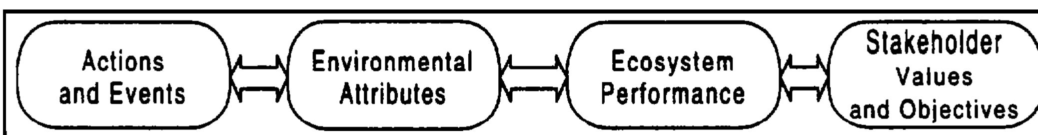


Figure 3.3. Elements of a conceptual framework.

The framework consists of a sequence of relationships. The flow of logic proceeds as follows: 1) any action taken by humans (or a natural event) within the ecosystem has some effect on attributes, or conditions, of the environment; these attributes may be abiotic (such as sediment loading or water temperature) or biotic (such as increases in abundance of a particular species by hatchery outplanting); 2) in turn, these changes in environmental attributes affect how populations within the ecosystem perform (i.e., survive and function); and 3) the resulting performance of populations creates an outcome that has direct relevance to societal objectives. The flow of information through these relationships is bidirectional-the process of planning, prioritizing and implementing actions is a cycle that proceeds from goals to actions repeatedly. The relationships are conceptualized in greater detail in Fig. 3.4.

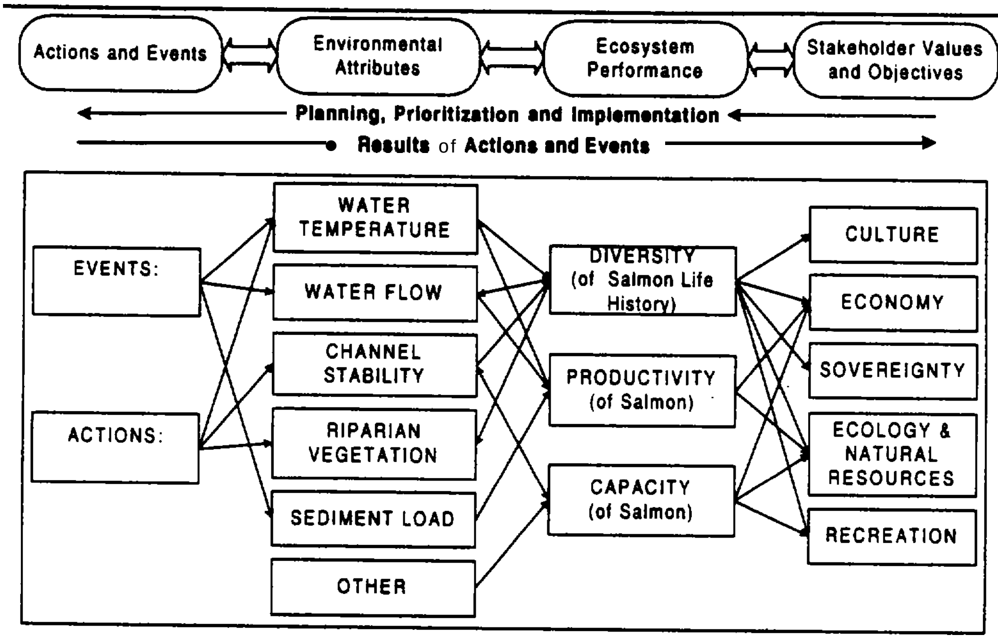


Figure 3.4. Framework relationships - salmon as an indicator speaes.

The purpose of this type of logical construct is to promote a better understanding of these relationships. Too often actions are presumed to translate more or less directly to objectives without a clear rationale of how their effects flow through the ecosystem. This framework requires explicit consideration of possible pathways.

The framework explains possible consequences in a manner consistent with existing knowledge and information, and it requires that all assumptions necessary to watershed planning be identified. It thereby becomes a vehicle for learning and communicating.

At the core of the framework are relationships between environmental attributes and biological performance. The term "biological performance" refers to the way in which a population manifests itself in space and time under a given set of environmental conditions. There is a wide array of possible performances (Warren et al. 1979) for species like salmon over the range of conditions that have existed in the Pacific Northwest.

The importance of spatial-temporal heterogeneity is embedded in Fig. 3.4. Actions ("what') take place in space ("where") and time ("when") dimensions, which in turn, have variable effects on environmental attributes over those same dimensions. An ecosystem perspective needs to incorporate these dimensions.

The framework implies that several levels of monitoring are necessary. The most direct means of monitoring should take place between actions and environmental attributes (Fig. 3.5). Most simply, do the proposed actions actually occur? If so, do they result in the changes to environmental conditions that are hypothesized or expected? For example, does the closure of a road reduce sediment input to the stream? This level of monitoring is relatively straightforward. Results can provide an effective and rapid way of learning and improving understanding within the adaptive management process.

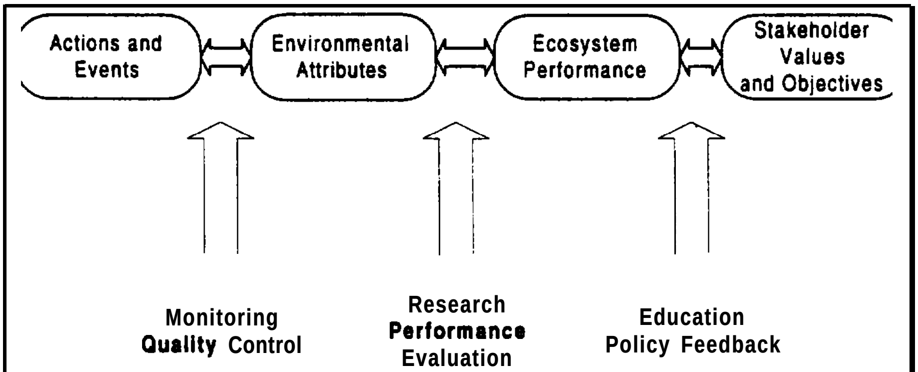


Figure 3.5. Monitonng levels.

Longer-term monitoring, which might more appropriately be labeled research, involves validating and learning more about the relationships between environmental attributes and biological performance (Fig. 3.5). It is unrealistic to expect that the monitoring of biological responses (for example by evaluating survival or abundance information) will be able to detect changes in performance attributable solely to the actions taken (Lichatowich and Cramer 1979). Well designed research should be used to improve understanding about the relationships between environmental conditions and population responses. Those results can then be used to modify how one views the effects of actions operating within the overall framework.

Another form of monitoring involves staying aware of the relationship between biological performance and objectives (or societal values) (Fig. 3.5). Values and objectives change over time. It is imperative that the management process routinely review, and revise as necessary, its understanding of the objectives toward which actions are ultimately being aimed.

Elements of Biological Performance

Biological performance is a central feature of the framework. It is defined in terms of three elements: life history diversity, productivity, and capacity (Fig. 3.6). These elements of performance are characteristics of the ecosystem that describe persistence, abundance and distribution potential of a population. From a broader ecosystem perspective the performance of indicator species may also reflect the potential for species diversity.

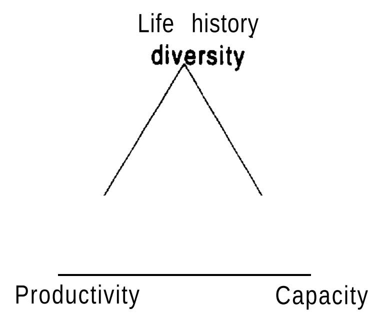


Figure 3.6. Conceptual elements of biological performance.

This conceptualization of performance provides a structure for applying basic ecological principles that affect the survival characteristics of populations. We use existing theory to link each of these elements to environmental conditions.

In population dynamics change is determined by four processes: birth, death, immigration, and emigration. These processes are regulated through *density-independent* and *density-dependent* mechanisms. These mechanisms are affected differently by environmental conditions (Moussalli and Hilborn 1986). As we examine some of these differences it is important to also remember that population responses are a result of interactions between the two mechanisms.

The distinction between density-independent and -dependent mechanisms is not always clearly understood (Begon and Mortimer 1986). Fig. 3.7a-b illustrates the distinction. A density-independent process is one in which the rate of response is not affected by population density (Fig. 3.7b), although, in the case of mortality, the number of deaths goes up as population size increases (Fig. 3.7a). In contrast, a density-dependent process is one in which the rate of response varies according to population density (Fig. 3.7b) due to competition for limited food and space resources; the number of deaths also goes up as population size increases (Fig. 3.7a).

The combination of these two processes results in the total mortality rate of a population at any given size. The effect of density-dependent mortality is low at low population densities, whereas density-independent mortality rate is constant across all population densities. It is important to note that the density-independent mortality rate regulates the rate of loss that a population can sustain; it is the determinant, for example, of the rate of harvest that a population can sustain.

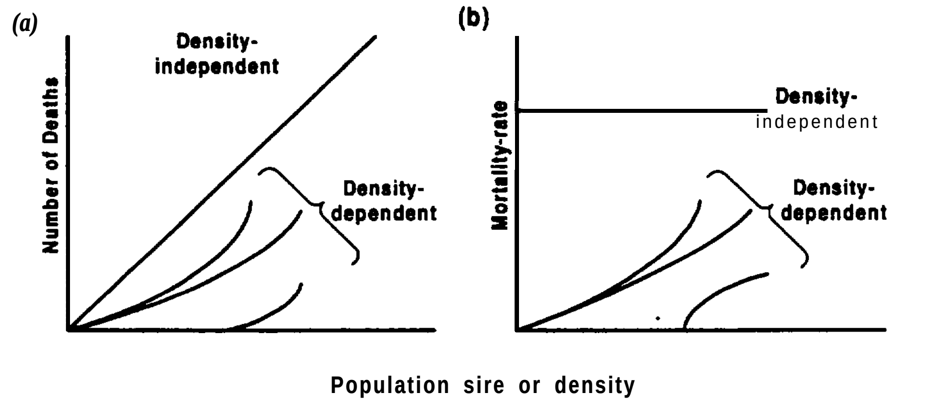


Figure 3.7(a,b). Density-dependent and density-independent relationships between population density and the number of deaths (a) and the corresponding mortality rate (b). The vertical axis in (a) is numbers, while in (b) it is rate. Taken from Begon and Mortimer 1986.

The identification of these two distinct mechanisms is useful in explaining the way in which various environmental conditions affect population performance. Habitat or environmental *quality* tends to affect density-independent processes (Moussalli and Hilbom 1986). A deterioration in habitat quality will therefore tend to increase density-independent mortality. For example, sedimentation of a salmon spawning bed will tend to operate in a density-independent manner, causing an increase in mortality rate at all population sizes. In this case, the quality of the spawning bed is determined by the amount of fine sediment passing through **or** entrained by the substrate.

In contrast, habitat *quantity* tends to affect density-dependent processes (Moussalli and Hilbom 1986). The amount of habitat available becomes increasingly important as population densities increase (i.e., as competition for limited resources increases). In a parallel example to the one above, the quantity of spawning beds available to a salmon population could be expected to contribute to the mortality of eggs as spawner densities increase to the point that some spawners dig their nests at the same sites as slightly earlier spawners. In this case, superimposition of nests causes mortality to eggs already deposited. But at very low spawner densities the chance of superimposition is very small.

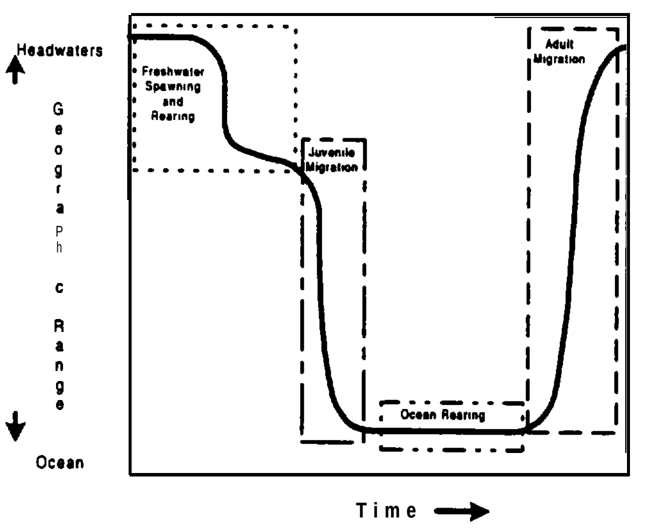
These mechanisms of density-independence and -dependence operate within the three elements that comprise performance. The mechanisms explain how changes in the quality and quantity attributes of the environment affect biological performance.

We next take a closer look at each of the three elements of performance: life history diversity, productivity, and capacity.

Life History Diversity. This element represents the multitude of pathways through space and time available to, and used by, a species in completing its life a chain of habitats having a sufficiently cycle. A salmon life history is comprised of favorable spatial-temporal distribution to enable its continuity (Thompson 1959). The life history encompasses many more or less distinct developmental life stages, each having its own set of environmental requirements (Bjomn and Reiser 1991). Species like salmon often exhibit a variety of life history patterns as a result of their adaptability to a heterogeneous and fluctuating environment. These life history patterns can be correlated with environmental variables on a spatial-temporal basis (Weavers 1993; Lichatowich and Mobrand 1995).

Populations that can sustain a wide variety of life history patterns are likely to be more resilient to the influences of environmental change. Diverse life history patterns dampen the risk of extinction or reduced production in fluctuating environments (den Boer 1968). Not all life history patterns will be affected uniformly by natural or man-caused perturbations. Thus a loss of life history diversity is an indication of declining health of a population (Lichatowich and Mobrand 1995) and perhaps its environment

The life history diversities of existing natural salmon populations can be described by the range of distributions and pathways that are used successfully by these populations. A pathway can be conceptualized as a trace or trajectory in space and time available to members of a population (Fig. 3.8). We use the term life history pattern to mean a collection of similar pathways.



'igure 3.8. Single life history trajectory partitioned into four distinct life tages.

A successful life history pattern is one that is brought to "closure" (Sinclair 1988); i.e., some individuals following the pattern survive through all life stages and return to their natal spawning ground. A sustainable life history pattern is one that remains successful over the range of prevailing environmental and man-induced mortality conditions.

Productivity. This element of performance represents the density-independent reproductive rate (or success) of a life history pattern over an entire life cycle. It is probably the most critical measure of the resilience of a life history pattern. It determines the rate of loss that can be sustained. Productivity can be likened to how far a rubber band can be stretched before breaking.

Surprisingly little attention has been given to the subject of salmon productivity within the literature (Hankin and Healey 1986; Moussalli and Hilborn 1986). Hankin and Healey (1986) suggest that biologists have given a disproportionate amount of effort to estimating habitat carrying capacity; greater need exists, they assert, to better understand productivity, especially as stocks decline.

The term "productivity" as used in this context follows the recommendations of Moussalli and Hilbom (1986) and Hilbom and Walters (1992). It refers to density-independent survival, as well as to what is often called the basic biological productivity of a population; i.e., the average number of eggs per surviving adult. The term is widely used in ecological and fisheries literature, where its meaning varies. Classical ecological usage usually relates to trophic productivity. In the fisheries literature it sometimes refers to total stock size. The meaning as applied in the EDT framework follows Moussalli and Hilbom (1986) precisely.

Productivity of salmon populations consists of distinct components (Fig. 3.9), each of which can have a significant effect on the overall value. Its two major components are reproductive potential and density-independent survival. Reproductive potential is the total number of eggs per adult spawner. This term is further comprised of two sub-components: average fecundity of females and average sex ratio of the spawning population. Density-independent survival is also made up of sub-components; e.g., freshwater and marine survival.

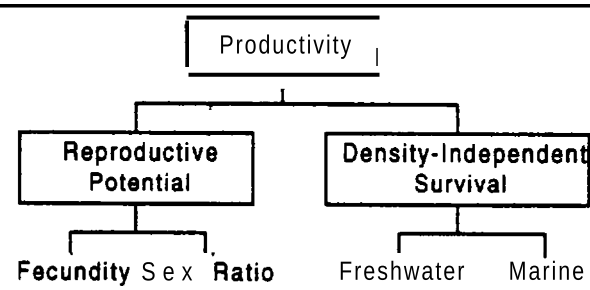


Figure 3.9. Components of productivity for salmon speaes.

An important property of productivity is that its components are multiplicative. This means that values for all of its separate components can be multiplied together to derive an aggregate or cumulative productivity value (see Example 1).

*** *Example 1 - Computing Cumulative Productivity* ******************************

Suppose a hypothetical salmon population has the following productivity characteristics on the average:

Eggs per female	**5,000**
Sex ratio (females per total spawners)	**0.33**
Freshwater density-independent survival	**0.15**
Marine density-independent survival	**0.10**

Cumulative productivity is then computed as follows:

(0.33 females/spawner)(5000 eggs/female)(0.15 smolts/egg)(0.10 adult returns/smolt) = 24.8 returns/spawner

** *End of Example 1* ***

A formula for productivity over an entire life cycle can be expressed as follows:

$$P_n = \prod_{i=1}^{n} p_i \qquad (1)$$

where P_n is the cumulative life cycle productivity over n life stages and p_i is the productivity for life stage i. This expression is simply all productivities through n successive stages multiplied together. Productivities for all life stages are expressed as density-independent survivals, except for the reproductive stage (at the start of egg incubation), which includes both survival and the average number of eggs per spawner.

This formula enables us to consider how environmental changes and harvest affect productivity and the implications for sustainability. Table 3.1 describes productivity characteristics of a hypothetical chinook salmon population under four sets of conditions: 1) initial conditions; 2) all survivals reduced by 50%; 3) altered sex ratio and. fecundity; and 4) additional reduction in freshwater survival by 25%. The life cycle is disaggregated into four life stages for the example: 1) egg incubation and freshwater rearing; 2) smolt migration; 3) ocean residency; and 4) adult migration back to the natal stream. Stage four represents adult migration within the river basin. We assume a single life history pattern for this hypothetical population (Fig. 3.8).

Changes in productivity associated with each scenario are displayed graphically in Fig. 3.10. Note that the Y-axis is displayed in log scale to better highlight differences between scenarios.

Table 3.1. Hypothetical prcductivity characteristics of a chinook salmon population under four sets of conditions.

Productivity conditions	Spawner sex ratio (m/f)	Eggs per female	Eggs per spawner	Density-independent survival				Returns per spawner
				Incubate & rear	Smolt migration	Ocean residency	Adult migration	
Initial	1.5/1	5,000	2,000	0.200	0.800	0.100	0.800	25.6
All survivals reduced 50%	1.5/1	5,000	2,000	0.100	0.400	0.050	0.400	1.6
Altered sex ratio and fecundity	2.0/1	4,000	1,600	0.100	0.400	0.050	0.400	1.28
Incubation and rearing survival reduced additional 25%	2.0/1	4,000	1,600	0.075	0.400	0.050	0.400	0.96

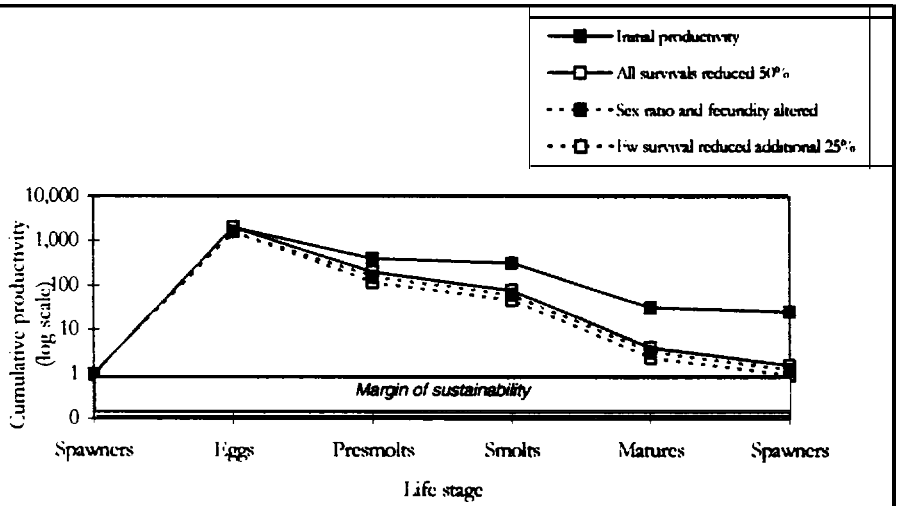


Figure 3.10. Effects of stage-specific productivity changes on the cumulative productivity of one spawner.

The values for initial conditions (for the population pictured in Fig 3.10) describe a fairly productive hypothetical spring chinook salmon stream located within the mid Columbia region.

Its historical productivity is computed to be 25.6 returns per spawner, a high value indicating a high amount of resiliency in this population. The theoretical minimum productivity required for sustainability is one, hence a life history pattern with a productivity of 25.6 would be highly resilient.

In the second scenario we assume that extensive environmental changes have occurred and there is harvest in the ocean. All survival rates were arbitrarily reduced by 50%. These survival reductions might, for example, be attributed to sedimentation of spawning beds, changes in the mainstem river affecang downstream and upstream migrations, and increased in-river and ocean harvest rates. The effect of these changes is a reduction of cumulative productivity by a factor far greater than 50%. Estimated productivity drops to 1.6 returning adults per spawner. Resiliency is marginally maintained above the critical level of 1.0. This sharp reduction in productivity is due to its multiplicative property, reflecting the cumulative effects of impacts occurring throughout the salmon life cycle.

CHAPTERS

The third scenario maintains the reduced survival rates but also changes the sex ratio of the spawning population and the average fecundity of females. Such changes have apparently occurred to many chinook salmon populations in the Pacific Northwest (Ricker 1981; Hankin and Healey 1986), due in part to effects of selectivity within fisheries. All fish within a population are not harvested at the same rate-fisheries tend to harvest sexes, fish sizes, and ages disproportionately. In our hypothetical case, productivity is reduced to about 1.3 returns per spawner, *further* diminishing resiliency.

The fourth scenario maintains the effects of the previous scenario but reduces freshwater survival by an additional 25%, driving productivity below 1.0 and making extinction inevitable.

An important point to be drawn from the fourth scenario is that exactly the same results would be obtained if the additional 25% loss occurred in any one of the four life stages. *In* fact, a 25 % change (increase or decrease) in productivity at any one stage produces a 25 % change in cumulative productivity. From a productivity perspective, there is no bottleneck-no single limiting factor.

Capacity. There is clearly some upper limit to the number of organisms that an environment can support due to finite amounts of space, food, or other needed resources (Ricklefs 1973). Capacity is the element of performance that detemines the effect of this upper limit on survival and distribution. It is the parameter that regulates the density-dependent population responses.

Superficially, the concept of capacity seems simple and easily envisioned. A room can hold only so many people. A tract of land can grow only so much wheat. A fish pond can be stocked with only so many fish. But the concept applied to an ecosystem is more elusive, particularly as it relates to species with complex life histories like salmon (Frissel et al. in press).

There have been numerous attempts to quantify or characterize the capacity of natural salmon systems (Burns 1971; Marshall 1980; NPPC 1991; Nickelson et al. 1993; Beechie et al. 1994). Most of these efforts are based on a capacity concept that focuses on a single life stage in isolation of others, as set forth by Burns (1971):

> ***"Carrying capacity is defined as the greatest weight of fishes that a stream can naturally support during the period of least available habitat.... The sham's carrying capacity limits the number and weight of salmonid smolts ultimately produced"***

This view is narrowly focused on the quantity of habitat during a single life stage. Such a view provides little useful information within a watershed or ecosystem context.

A different way of viewing capacity is needed if an ecosystem perspective is to be incorporated. From the perspective of a diagnostic species, such a view would necessarily consider the diversity of life histories used by that species. It would incorporate interactions of mortality factors pertaining to both quality and quantity of the environment, recognizing that they differ in space and time.

We propose a variation of the capacity concept that incorporates this complexity. It expresses capacity not as single quantity- there are too many interwoven life history strands in the ecosystem to do that in a meaningful and useful manner. Instead, it describes capacity as an index of the cumulative capacity of a life history pattern over its entire life cycle. The index provides a means of comparing abundance on a relative scale for different life history patterns.

We describe the concept through a series of four steps, each building on the previous one.

Step 1 - General Structure. We view the environment of the salmon as the chain of linked habitat segments within which its life cycle is completed (Thompson 1959, Paulik 1973). Each "link" in the chain represents a life stage, a location and a time period. If the "links" are small enough we may assume that they are uniform with respect to both environment and salmon life stage present. If we further assume that salmon survival within each "link" or stage in this 'multistage model is either density-independent or follows a Beverton-Holt type of survival function, then the survival for the full life cycle can be described by the Beverton-Holt function (Moussali and Hilbom 1986). Moussalli and Hilbom (1986) derive the capacity for the full life cycle, the cumulative capacity (C_n), for a multistage model of this type as a function of stage-specific productivities and capacities:

$$C_n = \frac{P_n}{\sum_{i=1}^{n} \frac{P_i}{c_i}} \qquad (2)$$

where c_i is the habitat capacity for life stage i, P_n is the cumulative productivity of n successive life stages, and P_i is the cumulative productivity of i successive life stages.

The expression for cumulative productivity (P_n) was given earlier in Equation (1); it is simply all productivities through n successive stages multiplied together.

The expression for cumulative capacity is derived from a Beverton-Holt multistage spawner-production relationship (Fig. 3.2). This particular production function has both intuitive and mathematical appeal. It provides a logical and reasonable structure for framing interactions of density-independent and -dependent processes under various environmental conditions. Moussali and Hilbom (1986) postulate that other standard production functions have similar characteristics.

Example 2 - Applied to One Life History Segment *******************

To illustrate the utility of this structure, we first apply it to one segment of a life history. For simplicity, the segment here is comprised of three life stages: 1) spawning and egg incubation; 2) fry colonization and summer rearing; and 3) over-wintering. Our example is based on coho salmon.

From Equation (2), the expression for cumulative capacity over three successive life stages can be written as:

$$C_3 = \frac{p_1 p_2 p_3}{\frac{p_1}{c_1} + \frac{p_1 p_2}{c_2} + \frac{p_1 p_2 p_3}{c_3}},$$

or, after simplifying:

$$C_3 = \frac{p_2 p_3}{\frac{1}{c_1} + \frac{p_2}{c_2} + \frac{p_2 p_3}{c_3}}$$

This expression shows how cumulative capacity is related to the productivity and capacity of the environment in all intermediate life stages (note that the productivity of the first stage cancels out of the equation).

In our example we use capacity estimates for coho salmon as derived experimentally by Nickelson et al. (1993); additional related material is found in Lestelle et al. (1993b). The estimates are based on the amount of "key" habirat available within the time periods encompassing each life stage and the maximum densities of fish found experimentally to utilize such habitat. Not all stream habitat is equally used by salmonids across their life history. For example, coho eggs are spawned in riffles, not pools, whereas summer rearing largely occurs in pools, not riffles.

Capacities and productivities for the three life stages used in the example are listed in Table 3.2 (values are hypothetical, meant for illustration only). The cumulative productivity for initial conditions of this life history segment is computed to be 156; i.e., 156 smolts would be produced per spawner in the absence of any density-dependent mortality. Cumulative capacity is computed to be 6,944, representing the largest potential number of fish (smolts) produced over the three intermediate life stages. Note that this value is considerably less than the stage-specific capacity for the third life stage (overwintering).

Table 3.2. Stage-specific productivities (p) and capacities (c) and resulting cumulative productivity and capacity through three freshwater life stages of a hypothetical coho salmon population.

Life stage	Capacity c	Productivity: Eggs/spawner	Productivity: DI survival	Productivity: P
Spawning & incubation	1,000,000	1,250	0.5	625
Colonization and rearing	50,000		0.5	0.5
Overwintering	10,000		0.5	0.5
Cumulative productivity (smolts per spawner)			156.3	
Cumulative capacity (smolts)			6,944	

The effects of hypothetical alterations of the environment on cumulative capacity can be examined by changing stage-specific capacities and productivities individually, then together. In the following we will change one life stage at a time. We examine three levels for each parameter value: a 50% reduction from initial conditions, no change, and a 50% increase over initial conditions. Such levels of changes to stage-specific productivity and capacity may be quite reasonable, given the kinds of environmental alterations to which streams in the region are subjected.

The results of these modifications, expressed as a percent change from initial conditions, reveal the sensitivity of cumulative capacity to changes in both the quality or quantity of the environment at any intermediate life stage (Table 3.3). The results will vary depending upon the characteristics of the initial conditions.

Table 3.3. Effects of altering life stage-specific productivities (p) and capacities (c) on cumulative capacity (as percent change from unaltered state) through three freshwater life stages.

Spawning and incubation life stage altered

Percent change in life stage *c*	Percent change in life stage *p*		
	-50	0	50
-50	-2.7	-2.7	-2.7
0	0.0	0.0	0.0
50	0.9	0.9	0.9

Colonization and rearing life stage altered

Percent change in life stage *c*	Percent change in life stage *p*		
	-50	0	50
-50	-23.4	-21.7	-21.2
0	-2.7	0.0	0.9
50	6.9	10.2	11.3

Overwintering life stage altered

Percent change in life stage *c*	Percent change in life stage *p*		
	-50	0	50
-50	-50.0	-41.0	-37.2
0	-23.4	0.0	11.3
50	-6.9	30.1	50.0

** *End of Example 2* ***

Step 2 - Incorporation of Life History Closure. Ultimately environmental capacity for a population must be considered over the entire life cycle of the animal. To consider capacity at the close of an intermediate life stage (as in the example above) ignores the effects of subsequent stages to population survival. Our interest in the performance of salmon, whether we view it as a direct or indirect indicator of deliverable societal values (Fig. 3.4), is long-term and most certainly includes the full life cycle.

While cumulative productivity is the same no matter where we define the beginning and end of a complete life cycle, cumulative capacity does depend on how we make this choice. A logical reference point along the timeline of life history for defining the unit of capacity for salmon populations is at reproduction. For salmon, spawning is the point where one generation ends and another begins. It is the point of minimum abundance in the life cycle and, therefore, represents the total amount of genetic material passed from one generation to the next.

This point along the life cycle is also most representative of the values ascribed to salmon populations by society over the long-term. It is adult salmon, and not juveniles, that relate most directly to societal values.

The computation of cumulative capacity at the closure of a life cycle is easily made using Equation (2) by including all life stages, beginning at spawning and ending at spawning. Cumulative capacity is thus expressed in terms of spawners. Similarly, cumulative productivity is expressed as returning spawners per parent spawner (see Example 3).

****Example 3 - Incorporating Life History Closure ************************

We use the same example as before, but now we include the remaining life stages up to the point of spawning (Table 3.4). The example places the hypothetical stream within a large river basin, like the' Columbia River. The location within the basin is not important to the example.

Table 3.4. Initial stage-specific productivities (*p*) and capacities (*c*) and resulting cumulative productivity and capacity through the full life cycle of a hypothetical coho salmon population.

Life stage	Capacity *c*	Productivity: Eggs/spawner	DI survival	P
Spawning & incubation	1,000,000	1.250	0.5	625
Colonization and rearing	50,000		0.5	0.5
Overwintering	10,000		0.5	0.5
Smolt migration	100,000,000		0.9	0.9
Ocean residency	100,000,000		0.1	0.1
Upstream adult migration	1,000,000		0.9	0.9
Prespawning	1,000		0.9	0.9
Cumulative productivity (spawners per parent spawner)			11.4	
Cumulative capacity (spawners)			336	

Life stages following overwintering are smolt migration, ocean residency, upstream adult migration, and prespawning. The initial values for these life stages are set for illustrative purposes only; they are not meant to reflect present-day values. The importance of the capacity values for migration and ocean stages is that they are very large compared to other stages.

Under the initial environmental conditions (Table 3.4), the cumulative productivity over the entire life cycle is computed to be about 11; i.e., 11 spawners would return per parent spawner in the absence of any density-dependent mortality. Cumulative capacity is computed to be 336 spawners.

Effects of hypothetical alterations of the environment are examined in Tables 3.5-3.7. First we reduce capacity by 25% for the four life stages within the spawning and rearing stream. This results in a drop in cumulative capacity, but note that cumulative productivity remains unchanged (Table 3.5).

Table 3.5. Effects of reducing stage-specific capacities within the natal stream by 25% on cumulative productivity and capacity (see Table 3.4).

Life stage	capacity c	Productivity		
		Eggs/spawner	DI survival	P
Spawning & incubation	750.000	1,250	0.5	625
Colonization and rearing	37,500		0.5	0.5
Overwintering	7,500		0.5	0.5
Smolt migration	100.000.000		0.9	0.9
Ocean residency	100,000,000		0.1	0.1
Upstream adult migration	1,000,000		0.9	0.9
Prespawning	750		0.9	0.9
Cumulative productivity (spawners per parent spawner)			11.4	
Cumulative capacity (spawners)			252	

Table 3.6. Effects of reducing stage-specific productivities within the natal stream by 30% combined with changes in stage-specific capacities from Table 3.5 on cumulative productivity and capacity (see Table 3.4).

Life stage	Capacity c	Productivity		
		Eggs/spawner	DI survival	p
Spawning & incubation	750,000	1,250	0.35	436
Colonization and rearing	37,500		0.35	0.35
Overwintering	7,500		0.35	0.35
Smolt migration	100,000,000		0.90	0.90
Ocean residency	100,000,000		0.10	0.10
Upstream adult migration	1,000,000		0.90	0.90
Prespawning	750		0.63	0.63
Cumulative productivity (spawners per parent spawner)			2.7	
Cumulative capacity (spawners)			177	

Table 3.7. Effects of reducing stage-specific productivities outside the natal stream by 30% combined with changes in Table 3.6 on cumulative productivity and capacity (see Table 3.4).

Life stage	Capacity c	Productivity Eggs/spawner	DI survival	P
Spawning & incubation	750,000	1,250	0.35	438
Colonization and rearing	37,500		0.35	0.35
Overwintering	7,500		0.35	0.35
Smolt migration	100400,000		0.63	0.63
Ocean residency	100,000,000		0.07	0.07
Upstream adult migration	1,000,000		0.63	0.63
Prespawning	750		0.63	0.63
Cumulative productivity (spawners per parent spawner)			0.9	
Cumulative capacity (spawners)			72	

Next we reduce productivity by 30% for the same stages. This results in another drop in cumulative capacity as well as a sharp decline in cumulative productivity (Table 3.6). The resiliency of the population is reduced.

Finally, we reduce survival for the previously unaltered stages by 30% (Table 3.7). Again, both cumulative capacity and productivity are reduced. Productivity is now less than one, a condition that would lead to extinction.

An interesting and important conclusion that emerges from this full life cycle perspective is that a population may be at capacity (in the cumulative sense) without a single component life stage being "fully seeded." Thus diagnoses that habitat is "under-seeded" or "fully seeded," unless analyzed from a full life cycle perspective, can be very misleading. We should be aware of such inconsistencies when we hear questions such as: Is the rearing capacity of a salmon stream fully seeded? Is the mainstem Columbia River being utilized at its potential capacity? Is the Columbia River estuary currently at its potential capacity? Is the North Pacific Ocean at its potential limit for salmon? All of these questions view life stages as independent of one another, which they clearly are not.

***End of Example 3 ***

Step 3 - Adaptation to a Complex Life History Pattern. The structure described thus far for capacity provides a useful way to improve understanding about factors affecting the relative sizes of salmon populations. However, it still does not adequately address variations within life stages and how life stages are connected in space and time. So far we have assumed homogeneity of conditions within a life stage. We have also assumed that all survivors of one life stage advance as one unified group, having identical characteristics, to the next life stage where they are again confronted with homogenous conditions.

The conditions of watersheds are not homogenous, however. Salmon following different pathways through watersheds encounter a wide range of conditions within individual life stages. The mosaic of environmental conditions within a watershed will have differing effects on salmon life history patterns.

In order to deal with the distribution of fish among pathways and through time along the pathways, we must make some further accommodations in our structure to allow calculation of cumulative capacity. Note that this problem does not exist for cumulative productivity, which is a simple product of all component productivities along each pathway. Cumulative capacity, on the other hand, incorporates habitat segments along pathways that may vary substantially in size. Timing along the pathways may also vary greatly. These complications require an adaptation of the cumulative capacity concept to incorporate life history pathways in space and time.

We address this problem first by defining a standard unit of habitat. This unit consists of a one meter band across the width of a waterway. A stream, river, or any body of water can thus be partitioned into a series of one meter bands of varying widths. Their widths are determined by the wetted widths of the channel (Fig. 3.11). Let us assume that the entire stream-river continuum from its mouth to its headwaters is comprised of such bands. All branches of it, regardless of size and location, are included. The concept is applied to the ocean environment, as well.

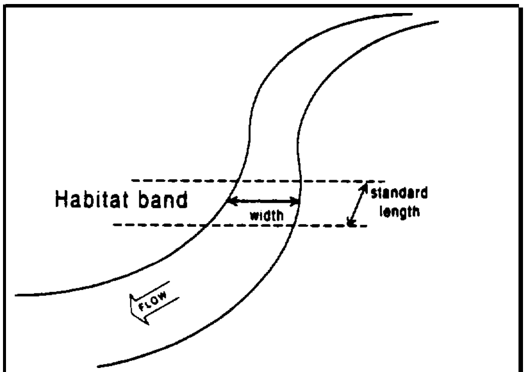


Figure 3.11. Dimensions of habitat band.

We can think of a salmon life history pathway as a trajectory through adjoining habitat bands over its entire range, including the ocean. These bands form a continuous chain of habitats of equal lengths, but varying greatly in band widths. The width of a habitat band may range from scarcely one meter in small headwater streams to hundreds of thousands of meters in the ocean.

Analogously to the way we viewed the life cycle as composed of several component stages, we now partition each stage into many one meter bands and many shorter time units. We assume that stage capacity for each habitat band is disaggregated into *m* successive sub-stages in order to express time in shorter units than those equivalent to entire life stages. This provides the needed resolution in the overall structure to describe a cumulative capacity for the entire chain of bands comprising a life history trajectory.

The capacity of a band (*BC*) can be described for each relevant life stage *i* as follows:

$$BC_i = \frac{P_i}{\sum_{j=1}^{m} \frac{P_j}{bc_j}} \tag{3}$$

where P_i is the cumulative productivity for *m* sub-stages and bc_j is the band capacity in the *j*th sub-stage.

Note that P_i is the cumulative productivity within the band, over m sub-stages. Therefore P_i is simply equal to p_i, the productivity for stage i, as applied in Equation (1).

If we assume equal productivity for each sub-stagej , p_j is equal to the jth root of the productivity for stage i as follows:

$$p_j = \sqrt[j]{p_i} \tag{4}$$

even if the values for p_j vary by sub-stage, their product will equal p_i.

The individual band capacities for each sub-stage can be estimated as generally described in Step 1; more precisely the capacity for a single substage j can be expressed as:

$$bc_j = width_j x keyhab_j x maxden_j \tag{5}$$

where $width_j$ is the width of the stream channel for the band of interest during the time period associated with sub-stage j, $keyhab_j$ is the proportion of key habitat (preferred or needed habitat) of the total habitat available during the time period associated with sub-stage j, and $maxden_j$ is the maximum density of the species within the key habitat during the time period associated with sub-stage j.

The three inputs needed to estimate band capacity during any time period are relatively straightforward to measure or derive. Channel widths can be obtained through measurement for representative stream reaches. These data exist for most streams in the Northwest. Band widths can easily be estimated by extrapolation from survey data over representative reaches and adjusted to reflect known or assumed changes in the hydrograph. Proportions of key habitat are derived in the same manner. Values for maximum densities associated with key habitat can be reasonably derived using the approaches generally described in Reeves et al. (1989) and Nickelson et al. (1993). These values can be scaled to account for changes in maximum density as a function of expected changes in fish size.

Equations (3), (4) and (5) then permit the estimation of the capacity of a habitat unit equivalent to a band unit for any life stage i but comprised of different bands for different sub-stages. This considers that a life history trajectory may cross many bands during the course of the life stage.

Estimates of band capacity (BC) for each life stage i can then be used in Equation (2) in place of stage capacities (c) giving the following expression for cumulative band capacity, here referred to as the cumulative capacity index (CI_n) over n stages:

$$CI_n = \frac{PI_n}{\sum_{i=1}^{n} \frac{P_i}{BC_i}} \quad (6)$$

where $PI_n = P_n$. Note that we refer to the calculated cumulative productivities and capacities as indices. They are relative not absolute estimates. The index is a descriptor of the relative capacity of an individual life history trajectory where that trajectory is defined initially according to its beginning point in a watershed. A beginning point is a location where reproduction occurs and eggs are deposited. All life history trajectories are therefore unique in that they begin in specific geographic locations then follow unique pathways in space and time. The index enables us to compare the relative cumulative capacities for different life history trajectories, where sizes of habitats used differ in width (see Example 4).

Example 4 - Including Complex Life History Patterns *********************

We now expand the example used in Steps 2 and 3 further to illustrate how cumulative capacity can be expressed for different life history patterns. Recall that the example places the modeled stream (a subbasin) within a much larger river basin, like the Columbia River. A salmon population (coho) is assumed to exhibit a number of life history patterns within the subbasin. For the sake of simplicity, the example looks at five sample life history patterns.

Each sample life history pattern is represented by a trajectory in space and time (Fig. 3.12). The five trajectories (identified as A-E) originate at different points along the stream; e.g., spawning occurs in the lower portion of the stream for trajectory A, whereas it occurs in the headwaters for trajectory E. Life history patterns that resemble these are known to exist for coho salmon (Lestelle et al. 1993a) and spring chinook salmon (Mobrand et al. 1995). For the example, the five life history patterns converge outside the subbasin, thereafter following the same general path until they again diverge when prespawners separate to go to their respective natal locations (Fig. 3.12).

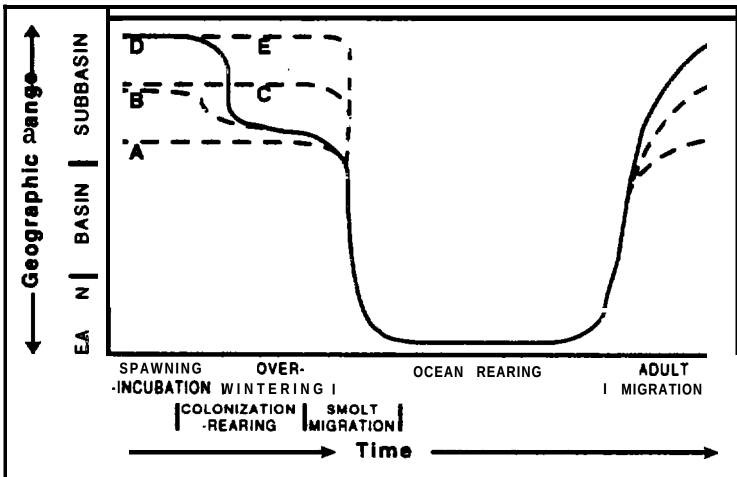


Figure 3.12. Multiple life history trajectories are partitioned into distinct stages. Five trajectories A-D are shown. Trajectory D is represented by a solid curve the others by dotted ones.

We partition the stream within the subbasin into a set of distinct reaches on the basis of environmental condinons. We use five reaches in our example. We also assume that information exists that allows us to characterize each reach in terms of attributes that determine stage-specific capacities and productivities. This information tncludes the physical dimensions of a reach and the proportion of key habitat by life stage in each. The values used for the maximum densities (fish/m^2) within key habitat at the end of each life stage were based on data contained in Nickelson et al. (1993) and Lestelle et al. (1993b).

The results of this exercise are summarized in Table 3.8. Values for band capacity at each stage within the subbasin were computed from Equation (5). Band capacities outside the subbasin were set arbitrarily high.

Indices for cumulative capacity and cumulative productivity can be computed using Equations (6) and (1) for each of the life history trajectories (Table 3.8). Values of the indices differ dramatically between trajectories. Trajectory A, with all life stages in the subbasin occurring in the lower reach (Fig. 3.12), has the largest index of cumulative capacity. though its cumulative productivity suggests that this life history pattern is barely sustainable under the given survival conditions. The lower reach is characterized as being highly suited for overwintering, whereas conditions for summer rearing (low density-independent survival) are unfavorable (perhaps due to high temperatures).

In contrast, trajectory E, which remains high in the stream, has a cumulative capacity index value that is only 3% of that for trajectory A. Its very low cumulative productivity indicates that this life history pattern is not sustainable. Conditions in this reach are not favorable for survival. However, trajectory D, with spawning and rearing maintained high in the system but overwintering occuring in the lower reaches, has much higher cumulative capacity and productivity. Trajectories B and C, which originate in the mid portion of the stream, also exhibit high index values for cumulative capacity and productivity.

Table 3.8. Stage-specific productivities (p) and capacities (c) and resulting cumulative productivity and capacity indices through the full life cycles of five life history patterns of a hypothetical coho salmon population.

Life stage	Band capacity *bc*	Productivity Eggs/spawner	DI survival	*p*
Within subbasin				
Spawning & incubation				
Reach 1	3,200	1,250	0.3	375
Reach 2	3,600	1,250	0.4	500
Reach 3	3,600	1,250	0.4	500
Reach 4	3,840	1,250	0.4	500
Reach 5	2,800	1,250	0.3	375
Colonization and rearing				
Reach 1	9.8		0.2	0.2
Reach 2	7.8		0.4	0.4
Reach 3	6.2		0.5	0.5
Reach 4	3.9		0.5	0.5
Reach 5	1.3		0.3	0.3
Overwintering				
Reach 1	4.0		0.5	0.5
Reach 2	2.4		0.4	0.4
Reach 3	2.4		0.4	0.4
Reach 4	1.0		0.2	0.2
Reach 5	0.1		0.2	0.2

(continued on next page)

Table 3.8 contnued.

Life stage	Band capacity *bc*	Productivity Eggs/spawner	DI survival	*p*
Smolt migration				
Reach 1	100		1	1
Reach 2	75		1	1
Reach 3	75		1	1
Reach 4	60		1	1
Reach 5	35		1	1
Outside subbasin				
Smolt migration	>10,000		0.6	0.6
Ocean residency	>1,000,000		0.1	0.1
Upstream adult migration	>500		0.6	0.6
Within subbasin				
Prespawning				
Reach 1	5.0		0.95	0.95
Reach 2	3.8		0.95	0.95
Reach 3	3.0		0.95	0.95
Reach 4	2.4		0.95	0.95
Reach 5	1.4		0.95	0.95

Life History Trajectory	Cumulative productivity index	Cumulative capacity index
A	1.3	0.072
B	3.4	0.065
C	3.4	0.041
D	2.9	0.044
E	0.8	0.002

*** *End of Example 4* ***

Step 4 - Incorporation of Interaction Between Jife Historv Patterns. The cumulative capacity index provides a way of comparing capacities of individual life history patterns by viewing the patterns independently of each other. Ultimately, we need to consider how these life history patterns interact with one another in areas where they overlap. Fish that follow different life history patterns may compete in those areas where their paths coincide. Such interactions affect the cumulative capacities and productivities of both life history patterns.

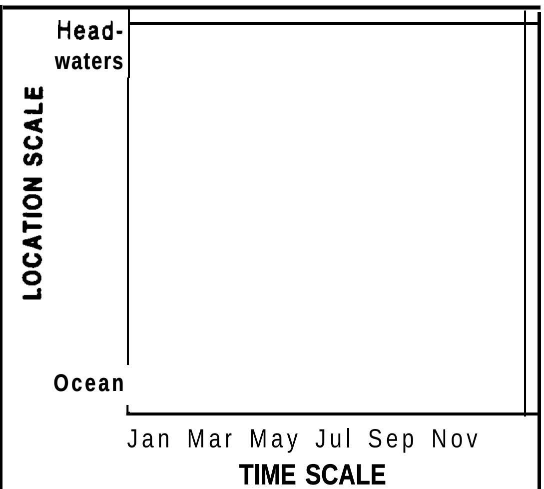
Conceptually, these types of interactions can be incorporated through a modeling exercise. To do so, we must first define all life history patterns and their constituent trajectories. Trajectories associated with each pattern would need to reasonably encompass the ranges of pathways comprising each pattern.

We leave out the details of the modeling approach in this discussion. The model is conceptually simple, but dimensionally complex. It includes all potentially interacting populations, patterns and trajectories. In order to incorporate interaction among coinciding populations, assumptions must be made about their relative abundance. We accomplish this by making an equilibrium assumption. In other words, we assume that the abundance and distribution pattern is that which would result if the system remained constant over a long period of time.

Organizing and Visualizing Information

In order for the framework to be useful, it must not only reflect good science, it must also convey information clearly. It must be possible to communicate analytical results among technical experts, decision makers and the public without misunderstanding. The framework we have described in this chapter has many levels of complexity. As you will see in the next chapter we rely heavily on graphical representations to visually convey information.

The organization of the ecosystem over time and space provides the structure for the gathering, storing and displaying of information. The spatial scale consists of the connected sequences of stream reaches through which salmon pass as they complete their life cycles. The time scale is measured in weeks or months. When space and time are used as the axes of a coordinate system, a grid is created where each point represents a location at a given point in time (Fig. 3.13). Data and information associated with each time space interval can now be plotted as peaks and valleys across the grid creating a landscape of attribute or performance values. We refer to these landscapes, somewhat loosely, as fitness landscapes-they show characteristics of the habitat over time from the salmon's point of view. We display these landscapes in two ways: as contour maps and as three dimensional surface maps (see Figs. 4.3 and 4.4 in the next chapter). Life histories can now be shown as pathways (trajectories) across the landscape. There is one additional dimension to the data that must be accommodated; namely, salmon have different habitat requirements during different life stages. Habitat well suited for spawning may, for example, be poor winter rearing habitat. In other words, the fitness landscapes vary by life stage (Fig. 3.14). Since a life history pathway can only occupy one location at any time, the tiers in Fig. 3.14 can usually be collapsed (the time scale will coincide with the life stage scale (see Fig. 4.10, next chapter).



igure 3.13. Matrix showing the organization of dat y time period and location. This grid is the base c he fitness landscape, where each cell (time -locatic ntersect) contains information about habit onditions.

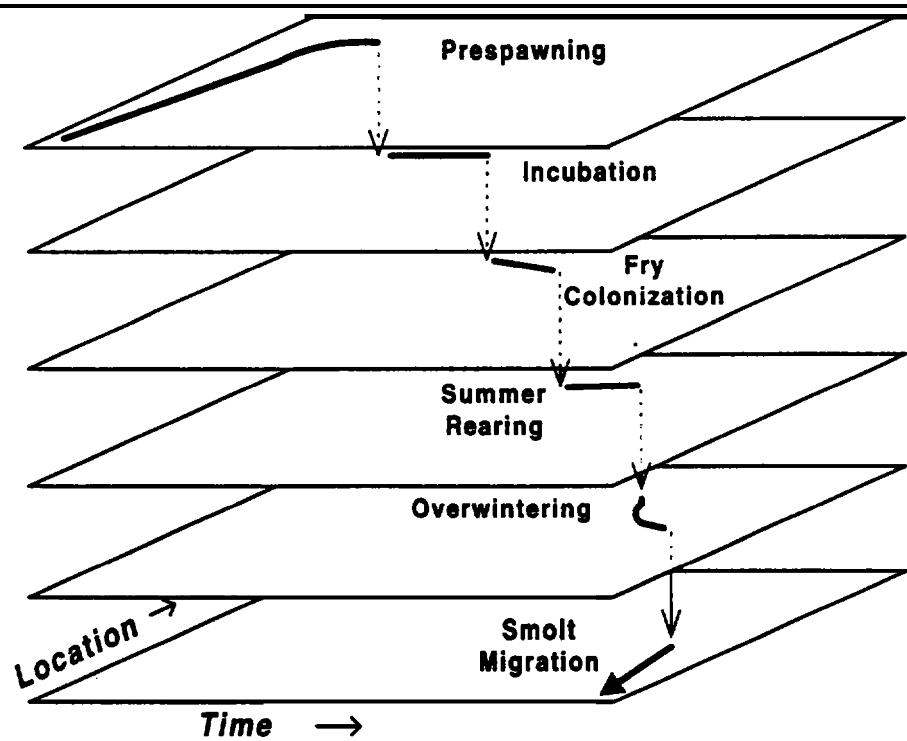


Figure 3.14. Visualization of a portion of a salmon life history. Each plane represents the survival conditions of one life stage The colored line shows a hypothetical life history pathway. Data describing capacity, productivity and environmental ataibutes are organized and displayed on these location versus time grids (the planes) and analyzed from the salmon perspective by tracing he values along life history pathways (colored line).

The fitness landscape representations let us view productivity and capacity profiles of multiple life history pathways simultaneously. This view is useful to the diagnosis; however, we also need to be able to integrate larger aggregates of salmon populations in the analysis. We need an overview of cumulative performance of many life histories. Fig. 3.15 is an example of how one might graphically combine information from several life histories on one plot. In this view a productive life history will appear to the right in the graphic, and large (high capacity) life histories will appear near the top. A healthy and diverse population will show many life history “points” in the upper right hand comer of the graph, whereas a weaker one will have its few point in the lower left comer. Fig. 3.15 can be used to make comparisons among populations and to view changes in populations over time. Performance requirements (“biological objectives”) to meet specified goals can be shown as clusters of points on the graph.

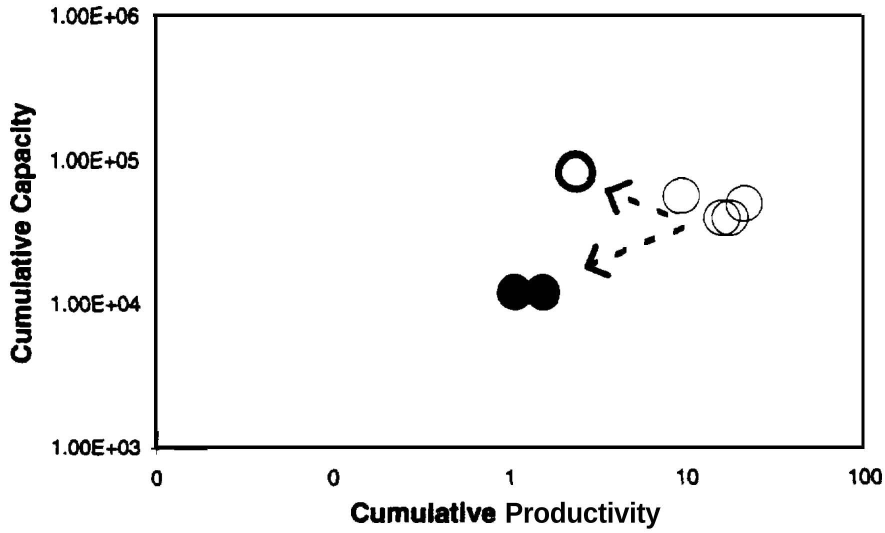


Figure 3.15. Visual representation of performance for a hypothetical salmon population. Filled circles represent present performance, open circles historic performance (the grey filled circle is a present life history that spends one life stage in a hatchery). The number and location of points on this graph indicate performance of the population aggregate.

In chapter four we will look in more detail at some of the tools we use to apply the EDT framework approach.

Chapter 4

ABOUT TOOLS

- Information Synthesis, Analysis and Visualization

"The value of modeling in fields like biology has not been to make precise predictions, but rather to provide clear caricatures of nature against which to test and expand experience."

– Carl Walters, *Adaptive Management of Renewable Resources*

A set of tools is needed to apply a theory. Tools are the procedures, analytical methods, and conceptual devices used to perform analyses and communicate results. They are the means for translating existing information and knowledge into the language of the conceptual framework for subsequent application.

Four categories of tools are described for the EDT analysis: 1) diagnostic methods; 2) treatment identification methods; 3) benefit and risk analysis procedures; and 4) a monitoring approach. These tools include procedures for capturing data (a database system), for analyzing information (models and analytical routines), and for displaying results (graphics and reports).

Diagnostic Tools

Diagnostic methods help us describe and interpret the condition of the watershed from the point of view of an indicator (or diagnostic) species[3]. The diagnosis consists of descriptive and an interpretive steps.

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[3]/The applications in this document use salmon as the diagnostic species, however the methodology is useful for describing the watershed from the perspective of any other species or economy. The more varied species or economies that are incorporated into the analysis, the more useful and informative the results will be.

Descriptive Analysis (PTA)

The first step in diagnosing watershed conditions is with what we call a Patient-Template Analysis (PTA) (Lichatowich et al. 1995). It is a comparison of existing environmental conditions (the Patient) to those of a model of health (the Template) from the perspective of the diagnostic species. The Template is a benchmark or reference point that defines healthy conditions within the natural limits of the ecological setting (e.g., geology, climate, and genetic "blueprints"). Lichatowich et al. (1995) proposed that historic conditions prior to major man-induced changes can serve as the Template.

As originally proposed, PTA can incorporate a variety of information (RASP 1992; Lichatowich et al. 1995) and can focus on individual elements of biological performance (Lichatowich and Mobrand 1995). Methods presented here provide a means for incorporating all three elements of performance: life history diversity, productivity, and capacity.

Procedures are presented in three steps: 1) information collection; 2) data compilation, summarization and analysis; and 3) graphical display.

About Collecting the Information. Relevant information should be assembled from whatever sources are available to help describe Patient and Template conditions. Specific informational needs must be translated into the terms of the' conceptual framework The process of gathering this information and translating it into useful terms is described below.

An important part of the information collection step is to obtain a general overview of the historic conditions of the relevant watersheds and their components. This is done by reviewing pertinent documents that describe that nature and extent of environmental changes that have occurred in the area of interest prior to major man-induced changes. Those changes relevant to the diagnostic species are to be the focus.

An overview can be made at different levels of thoroughness depending on availability of resources. It may consist of simply reviewing readily available reports and literature. If time permits, older documents, such as those located in rare book collections, can be particularly useful to describe environmental conditions as they existed in a relatively undisturbed state. The information can be summarized into a document to enable the various participants in the EDT process to review relevant material. Source documents should be referenced.

'The overview should give a perspective for how extensive environmental changes have been, generally when those changes occurred, and the types of land use activities associated with those changes. It should help to describe the major characteristics and features of the landscape prior to major environmental change. Some of the characteristics to be considered are riparian condition, flow patterns, stream temperature, in-stream habitat complexity, channel morphology and stability, and extent of adjacent wetlands and connected ponds. Each of these relates to the quality and quantity of the habitat used by the diagnostic species.

Workshop Forum. The use of workshops attended by knowledgeable individuals is the recommended means of obtaining the specific information needed for the analysis. The analytical procedures require that information be captured in a standard format. Local expertise and professional judgment pertaining to the environmental conditions and performance of the diagnostic species are required. The workshop forum has proven highly effective for these purposes.

Workshop attendance should include individuals with different expertise. Some individuals should be knowledgeable about habitat-life history relationships for the diagnostic species. Some need to 'be strongly familiar with local conditions of the watershed. Individuals who have overseen the collection of relevant habitat data should be also in attendance. It can be useful for participants to come from a variety of organizations and backgrounds. Workshops consisting of eight to sixteen participants have proven very effective. Participants at workshops held in Washington and Oregon have been employees in state, tribal, and federal agencies, as well as local landowners familiar with watershed conditions.

The participation of the group in the workshop needs to be facilitated by a person familiar with the overall EDT process and the theoretical basis for the analysis. The role of the facilitator, in addition to encouraging the participation of those in attendance, is to maintain consistency throughout the information collection process.

The workshop format should be structured to promote involvement by the participants. A format proven effective consists of three parts. Part one provides an overview of the conceptual framework and its major components. This helps to ensure that everyone is educated to the concepts involved Part two is a presentation of the historical overview of the watershed (as described earlier). Part three comprises the major portion of the workshop, consisting of the actual work of compiling the dam in a systematic fashion.

Workshops that we have conducted typically run for two days each. A series of workshops may be required to assemble all of the necessary information for an entire watershed.

The workshops do more than compile information. They serve as a learning tool for the participants. Participants typically find that insights are gained to better explain the current condition and distribution of the diagnostic species in watersheds of interest

System Organization. All of the information used in, or produced from, the PTA needs to be considered within spatial-temporal scales consistent with the range of possible life histories of the diagnostic species. This requires that spatial-temporal scales be defined accordingly.

As an example of spatial scale used, consider the Grande Ronde watershed located in northeast Oregon. The watershed is divided into separate units on the basis of the natural stream drainage system, as illustrated in Fii. 4.1. The schematic shows the drainage system broken into tributary and mainstem units used in the Grande Ronde analysis. The drainage units are not equal in size. Units are delineated by the connectivity of the drainage along stream channels using the EPA's stream reach numbering system as expanded by the Northwest Power Planning Council. For example, the sub-drainage of the Grande Ronde River upstream of Clear Creek is one unit (Fig. 4.1). It includes the entire catchment of that area. Clear Creek is another unit and includes its entire catchment The Grande Ronde River reach between Clear Creek and downstream to its confluence with LimberJim Creek defines another unit, which is treated as a separate catchment encompassing the drainage area surrounding this reach. This unit can be considered alone, but in combination with the two units upstream it defines a higher hierarchical level.

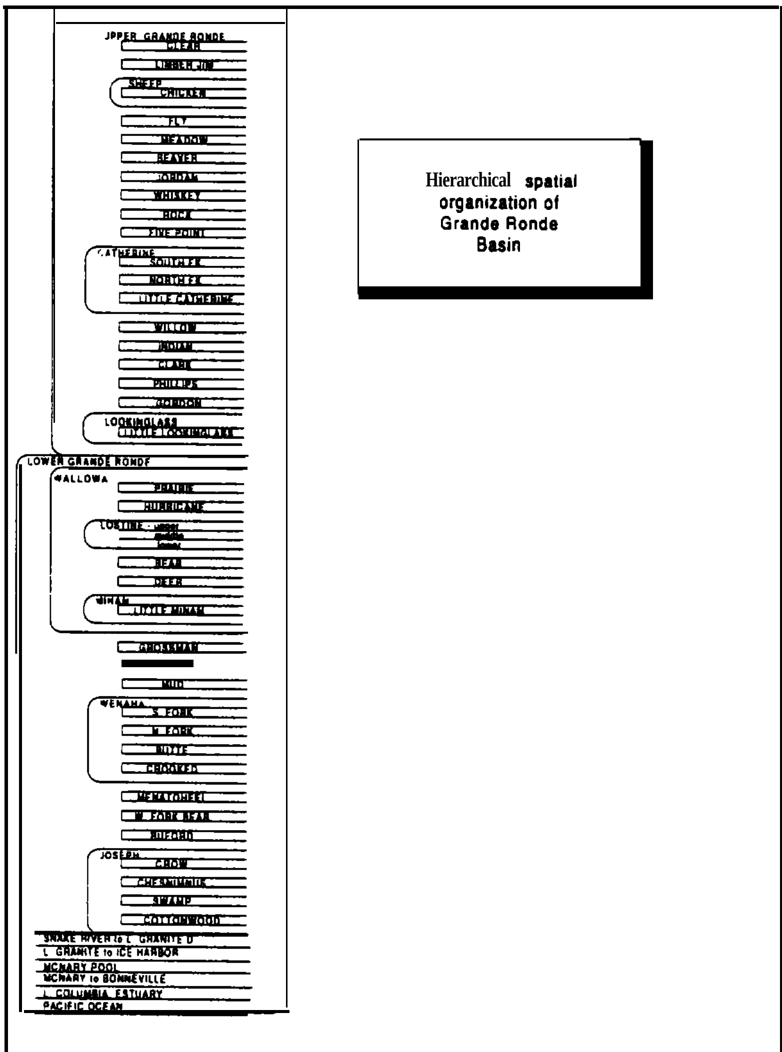


Figure 4.1. Spatial scale used for the Grande Ronde Basin framework.

Unit delineation in Fig. 4.1 shows the level of spatial organization selected for analyzing spring chinook within the Grande Ronde watershed. A finer level of organization has been used for coho salmon within Hood Canal basin watersheds in western Washington. Other scales may be required for other diagnostic species. Not shown in Fii. 4.1 is a unit delineation for areas downstream of the Grande Ronde drainage, which is needed to complete an analysis over an entire life cycle of salmon.

Time also needs to be divided into relevant units. For salmon species time is delineated within a calendar year by month and statistical week This scale is well suited for salmon species. Life stages of salmon can be identified as distinct developmental phases that have different environmental requirements. These stages can be defined by month or statistical week, as illustrated for nine life stages of spring chinook salmon within the Grande Ronde Basin (Table 4.1).

Much of the information used in formulating the diagnosis is displayed in a space-time format like that illustrated for the mainstem Grande Ronde River (Fig. 4.2). The figure illustrates format only and contains no other information. This format is used as a device to help visualize patterns of survival and the relative strengths of morality factors operating on the population in time and space. The format is particularly effective at showing how conditions that affect the performance of a population can vary dramatically within these dimensions.

Table 4.1. Definition of spring chinook salmon life stages within the Grande Ronde Basin and corresponding time periods.

Life Stage	Description	Months	Statistical weeks
Pre-spawning adult	Upstream adult migration and holding prior to spawning.	April-August	15-33
Spawning	Spawning period, including establishment and defense of redd sites.	August-September	33-38
Incubation	Egg deposition to fry emergence.	August-April	33-70
Fry colonization	Fry emergence until establishment of summer rearing locations.	April-June	61-71
Summer rearing	After colonization ceases when fish are largely stationary and activities are mainly directed at feeding and growth (large fish may outmigrate near end of period).	June-September	71-95
Fall redistribution and overwintering	Beginning with drop in temperature in early fall until the onset of yearling smolt migration at the end of winter.	September-March	96-114
Smolt to smolt	Onset of seaward migration to departure from the Grande Ronde Basin.	April-June	114-125

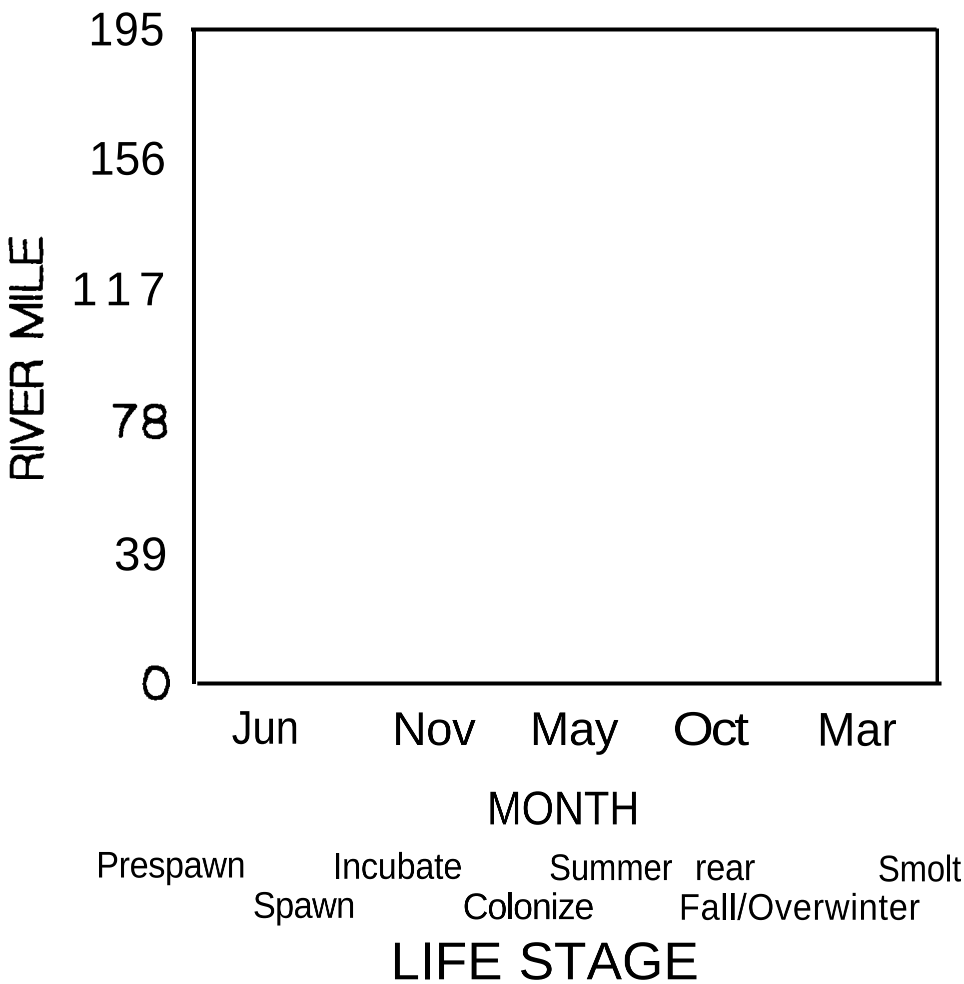


Figure 4.2. Space-time format for organizing diagnostic information for spring chinook salmon in the mainstem Grande Ronde River.

CHAPTER
About this Primer
About EDT
About Tasks
About Theory
About Tools
Diagnostic Tools
Descriptive Analysis(PTA)
Collecting Information
Analyzing Information
Displaying Information
Interpretive Analysis
eatment Identification Tools
enefit and Risk Analysis Tools
Ionitoring Tools

Assessment Measures Four measures are employed to assess the effects of environmental attributes on population performance:

- Relative productivity (or survival)
- Relative effect of environmental quality on productivity
- Total quantity of habitat
- Relative quantity of key habitat (or proportion of total)

The combination and interaction of these measures are used to describe population performance in relation to the unique set of environmental quality and quantity attributes of a watershed. Each measure, except one, is assessed in a relative manner to facilitate obtaining estimates of each. This simplifies the analysis. All measures are assessed for each life stage of the diagnostic species within each geographic unit

The assessment is made by following a set of consistent procedures for identifying and interpreting information relevant to each measure. The most effective means that we have found for performing the assessment is through the workshop forum described earlier. The procedures lead workshop participants to make inferences about the condition, or level, of each measure.

Inferences can be based on various sources of information. These sources may include the results of studies within the specific watershed of interest, personal observations of workshop participants, or other studies outside the basin. The inferences are assumptions that are necessary for assessing performance. The procedure requires that the basis of each assumption be stated and documented. These assumptions are recorded in the workshop process and subsequently stored as part of the database for future reference.

The power of this type of analysis is the requirement to explicitly consider, identify, and document all assumptions. The process of carefully considering these assumptions promotes critical thinking. Example forms used to perform the assessment are provided in the Appendix A.

Relative Productivity. This measure describes that element of performance referred to as productivity. It addresses mortality or losses due strictly to density-independent mechanisms.

Participants at the workshop assess relative productivity for the diagnostic species based on their knowledge of the environmental requirements considered optimal for the species and of conditions within the geographic units.

The measure is scored on a scale of O-l, where a value of 0 represents no survival and 1 represents optimal survival conditions (ignoring density effects) for the diagnostic species. If, for example, a river reach is given a value of 1 for one life stage, say egg incubation, this would mean that conditions in that reach are considered optimal for egg survival. Therefore, survival in the absence of density effects would be the highest possible for this life stage under natural conditions. If the reach is given a score of 0.5, then survival would be expected to be equivalent to 50% of the highest possible under natural conditions. If a score of 0 is given, then no survival would be expected for the stage.

Workshop participants also assess how the survival component varies, on the average, over the time period associated with each life stage. This is done for monthly intervals within the life stage. Each month is scored separately by assuming that survival conditions of that month are the worst for the entire life stage. This procedure allows estimation of when, and for what length of time, survival would be affected.

Subsequent to the workshop, the data are used to compute weekly relative survival rates for the duration of each life stage, using the monthly values to determine how survivals vary over the stage. Weekly survivals are assumed to be constant within months. Because survival rates are multiplicative, all weekly values for a life stage multiplied together equal the life stage productivity.

Relative Quality of Environmental Attributes. This measure explains, or justifies, the productivity scores by identifying the relative contributions of a range of environmental quality attributes to those scores. The measure describes how workshop participants rate the effects of environmental quality conditions within each geographic unit on life stage productivity.

Fourteen descriptive attributes of environmenral quality for salmon species have been employed (Table 4.2). All of these attributes are known to affect the density-independent survival of salmonids at one or more life stages. Three of these attributes (competitors, predators, and pathogens) are biotic factors representing non-diagnostic species and their effects on the diagnostic population. They are rreated as part of the environment affecting the diagnostic species.

The environmental quality attributes describe conditions within the stream environment or in its immediate vicinity, such as within the riparian condition. Many of the attributes also reflect conditions in the uplands, which can affect stream conditions downstream within the drainage. An analysis designed to focus on non-salmonid diagnostic species, particularly terrestrial species, may need to include other attributes.

Workshop participants score each quality attribute by identifying its relative contribution to the productivity scores. Attributes are scored on a scale of 0-4, where 0 indicates no contribution to downgrading survival (from optimal) and 4 indicates a lethal effect (Table 4.3). For example, if relative productivity was scored 1, indicating optimal conditions for survival are present, then all quality attributes must have been scored 0 (i.e., no deleterious attribute effects). If relative productivity was scored 0.5, indicating less than optimal conditions are present then at least one or more attributes must have been scored a 2 or 3 indicating a moderate or high effect on survival. If

Table 4.2. Description of environmental quality attributes affecting responses of salmonids within freshwater. This list was applied to spring chinook salmon in the Grande Ronde Basin; other attributes may be needed for other species or in different types of environments.

Attribute	Description
Channel stability	Stability of the reach with respect to its streambed. banks, and its channel shape. and location.
Flow	Pattern and extent of flow fluctuations within the stream reach.
Habitat type diversity	The extent of habitat complexity within a stream reach. Complexity is the opposite of uniformity; greater complexity increases density-independent survival; woody debris. brush. and other structure add complexity.
Sediment load	The amount of sediment present in, or passing through, the stream reach. Sediment may be suspended (turbidity), moving along the substrate (bedload). or within the substrate (percent fine particles).
Temperature	Water temperature in the stream reach. Density-independent survival is affected by rapid fluctuations, or by conditions near the extremes of tolerance.
Riparian condition	The state of the vegetation component of the narrow strip of land bordering the stream where vegetation species occur that are dependent on the stream or its adjacent water table.
Predators	The relative abundance of predators that feed upon the diagnostic species.
Chemicals	Concentrations of toxic chemicals from point and non-point sources.
Competitors	The relative abundance of other species in the stream reach that compete with the diagnostic species for food or space.
Obstructions	Physical structures that impede the use of a stream reach, such as dams, weirs, or waterfalls.
Withdrawals	Water withdrawals from the stream reach.
Nutrient load	The concentration of dissolved nutrients due to natural or man-induced causes. (Only nutrient loads that affect density-independent survival are considered here: hence, food enrichment for the diagnostic species is not addressed here.)
Oxygen	Mean concentration of dissolved oxygen in the stream reach.
Pathogens	The abundance, concentration, or effect of pathogens in the stream reach. For example, the presence of a fish hatchery or large numbers of livestock along the reach could cause unusually high concentrations of pathogens.
Other	Any other attribute unique to the stream reach that may affect survival.

Table 4.3. Numenc scores used in describing the relative effects of the quality of environmental attributes on the survival of diagnostic salmonid populations.

Relative quality	Score
Lethal effect	4
High effect	3
Moderate effect	2
Low effect	1
No effect	0

productivity was scored 0, indicating no survival would be expected, then at least one attribute must have been scored a 4 for a lethal effect

This procedure for identifying and scoring environmental quality conditions, while based on judgment, is a way of profiling the entire watershed using a systematic and consistent approach. It is particularly useful for diagnosis because it links environmental attributes directly to survival (productivity) values, facilitating identification **of** the specific attributes that need to be targeted if survival conditions are to be changed at specific locations and times.

***Quantity of Habitat*.** This measure quantifies the total amount of habitat available to be used by the diagnostic species within each geographic unit in each life stage, including areas that may not be highly preferred or utilized For spring chinook, total available habitat would consist of the total amount of stream area available to be used in each geographic unit and life stage. Stream area is computed as the product of stream length and average width (wetted area) by time period. The data needed for these computations are obtained from stream habitat databases.

This measure is used in conjunction with the relative quantity of key habitat (see next section) to analyze the distribution of habitat capacity, one of the three performance elements.

Relative Quantity of Key Habitat. This measure quantifies the amount of key habitat relative to the total amount available within each geographic unit in each life stage. Habitat requirements and preferences differ by species and often by life stage for those species. The key habitat measure is used as a way of examining habitat capacity in the diagnosis.

Key habitat is that component of the total habitat available to a species that is strongly preferred, or needed, during a life stage (shown for spring chinook in Table 4.4). For example, while salmon require a stream to live in, they also require riffles containing a certain sized substrate for spawning and reproduction. These spawning riffles are referred to as “key habitat" during both the spawning and egg incubation life stages. In this case, the measure would indicate the percentage of stream environment within a geographic unit that consists of spawning riffles suitable for chinook salmon at the appropriate time. The measure says nothing however, about the relative quality of spawning riffles for egg survival, which is described through the productivity measure.

The relative amounts of key habitat are determined according to five categories of availability using scores of O-4 (shown for spring chinook in Table 4.5). Here, a score of 0 indicates that no key habitat is present, whereas a value of 4 means that it is superabundant relative to total habitat present Use of categories of availability in this manner facilitates acquisition of information. Biologists who are knowledgeable about particular streams, even if no actual quantitative survey data exist, are usually confident about assigning scores at this level of resolution.

Table 4.4. Descriptions of key habitat used by spring chinook salmon by life stage within the Grande Ronde Basin.

Life stage	Key habitat
Pre-spawning adult	Large, deep pools with sufficient connecting flow for adult migration.
Spawning	Riffles containing a mixture of gravel and cobble sizes with flow of sufficient depth for spawning activity'.
Incubation	Riffles as described for spawning with sufficient flow for egg and alevin development.
Fry colonization	Shallow and relatively slow velocity areas within stream channel, often associated with stream margins and in relatively low gradient reaches.
Summer rearing	Pool type habitat associated with relatively low gradient stream channel reaches (usually not in backwaters nor slow eddies).
Fall redistribution/overwintering	Areas containing structural complexity (wood matrices, brush, or large cobbles) within flowing channel, not usually in swift or higher gradient reaches; off-channel areas (ponds, oxbows, etc.).
Smolt to smolt	Sufficient flow for free movement of smolts downstream.

Table 4.5. Relative quantity of key habitat for spring chinook within stream reaches of the Grande Ronde Basin.

Relative quantity of key habitat	Score	All stages except smolt to smolt[1]	Smolt to smolt life stage
Exceptionally high	4	more than 50% of stream area	Superabundance of needed flow
High	3	between 25% and 50% of stream area	Migration may be affected slightly
Low	2	between 5% and 25% of stream area	Migration affected noticeably by reduced flow
Scarce	1	less than 5% of stream area	Migration very difficult due to low flow
None	0	0% of stream area	Channel is dry

[1] Stream arca being referred to during fry colonization is the area along stream margins.

About Analyzing and Managing Information. AU data pertaining to system organization and the assessment measures need to be placed in a computerized database to facilitate summarization and analysis. The database software used for existing EDT applications is Microsoft Access 2.0. All numeric scores for the assessment measures, as well as related descriptive comments obtained through the workshops, are entered into the database. Hence the database serves as the repository for both the numeric scores and the assumptions made in assigning those scores.

The data are then formatted into the appropriate spatial and temporal scales for graphical purposes, which can be accomplished with a set of routines that operate within Microsoft Excel 5.0. Dam processing modules to facilitate this step are written in Visual Basic for Applications, Microsoft's macro language. Data are queried from the Access database and placed in Excel for processing. The analytical routines compute weekly values of relative survival and habitat capacity, which are subsequently used to construct visual displays of the information for diagnostic purposes. The routines place these data, as well as environmental attribute data, into the proper formats for the graphics software employed.

About Displaying Information: Visualizing the Landscape. The final step in the Patient-Template Analysis is to draw the information together into useful formats for comparing conditions between the Patient and Template. This is done by constructing a series of visual displays. The displays provide a way of visualizing performance-related patterns over scales of space and time relevant to the overall condition of the diagnostic species. They are produced using a set of smndardized formats to facilitate visualization and subsequent analysis.

The displays are generated with SYSTAT 5.0 for Widows or Microsoft Excel 5.0, depending on the graphic being made. Comrnand modules have been written that run each software application for making the displays.

Two types of displays can be generated to depict performance-related patterns across a watershed for the diagnostic species. The first type shows either productivity (i.e., density-independent relative survival) or capacity within a two dimensional display of space and time, consistent with Fii. 4.2. The second type projects a three-dimensional surface above the flat 2-D display to enhance visualization of patterns that may exist These displays are images of Patient and Template “landscapes” of density-independent survival and capacity for the diagnostic species. The second display, which combines both 2-D and 3-D formats, is particularly useful for visualizing changes in performance-related patterns between the Patient and Template.

Examples of these displays, using spring chinook salmon in the Grande Ronde River, are shown in Fii. 4.3 and 4.4. It is evident that significant changes have likely occurred in spring chinook productivity within this watershed between historic times and the present The figures emphasize the point that conditions for survival are not uniform across a watershed. Note that productivity here is expressed as relative density-

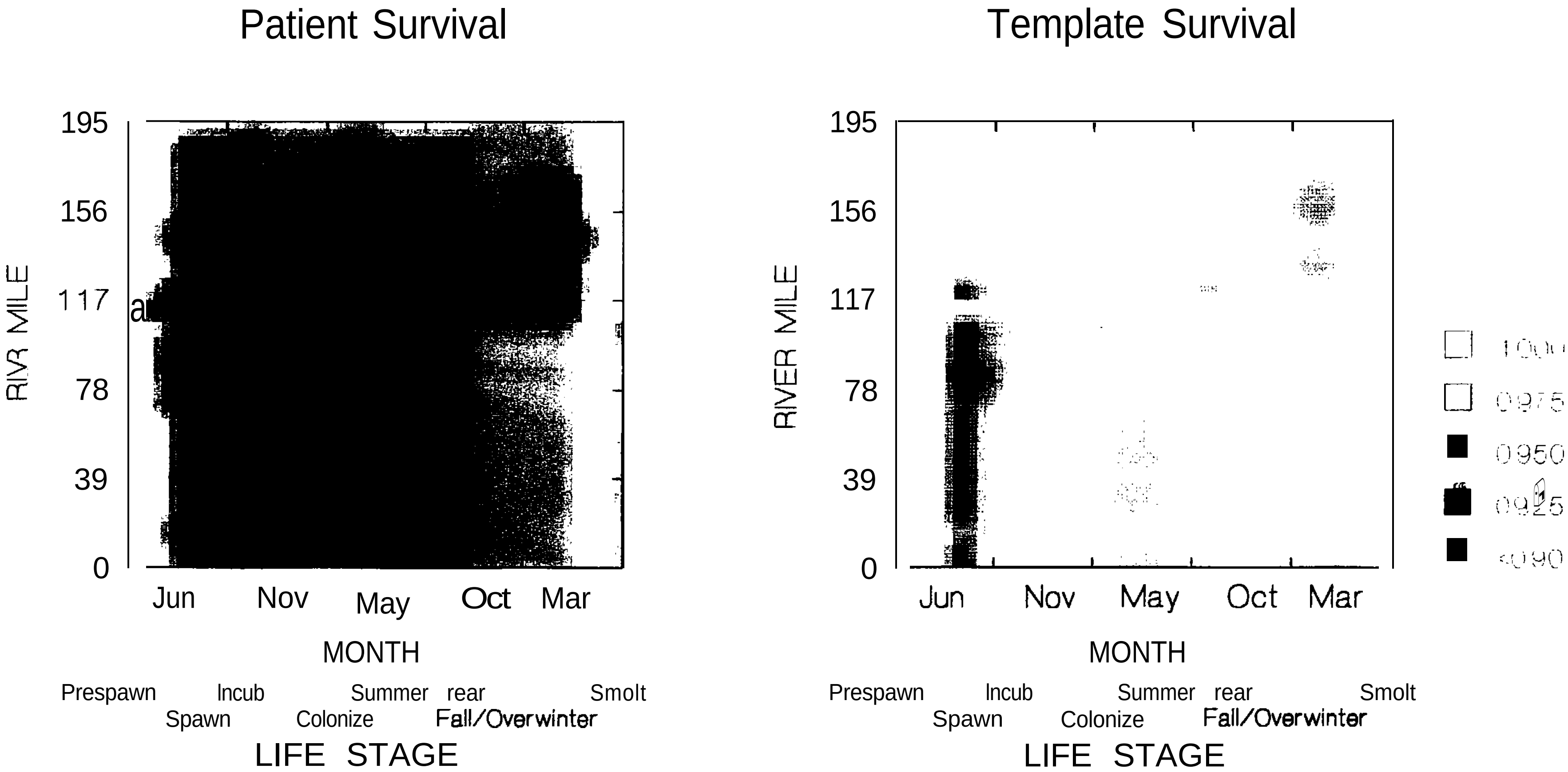


Figure 4.3. Relative productivity (density-independent survival) of spring chinook salmon by time and location in the mainstem Grande Ronde River. Data are displayed in a color-shaded contour map format

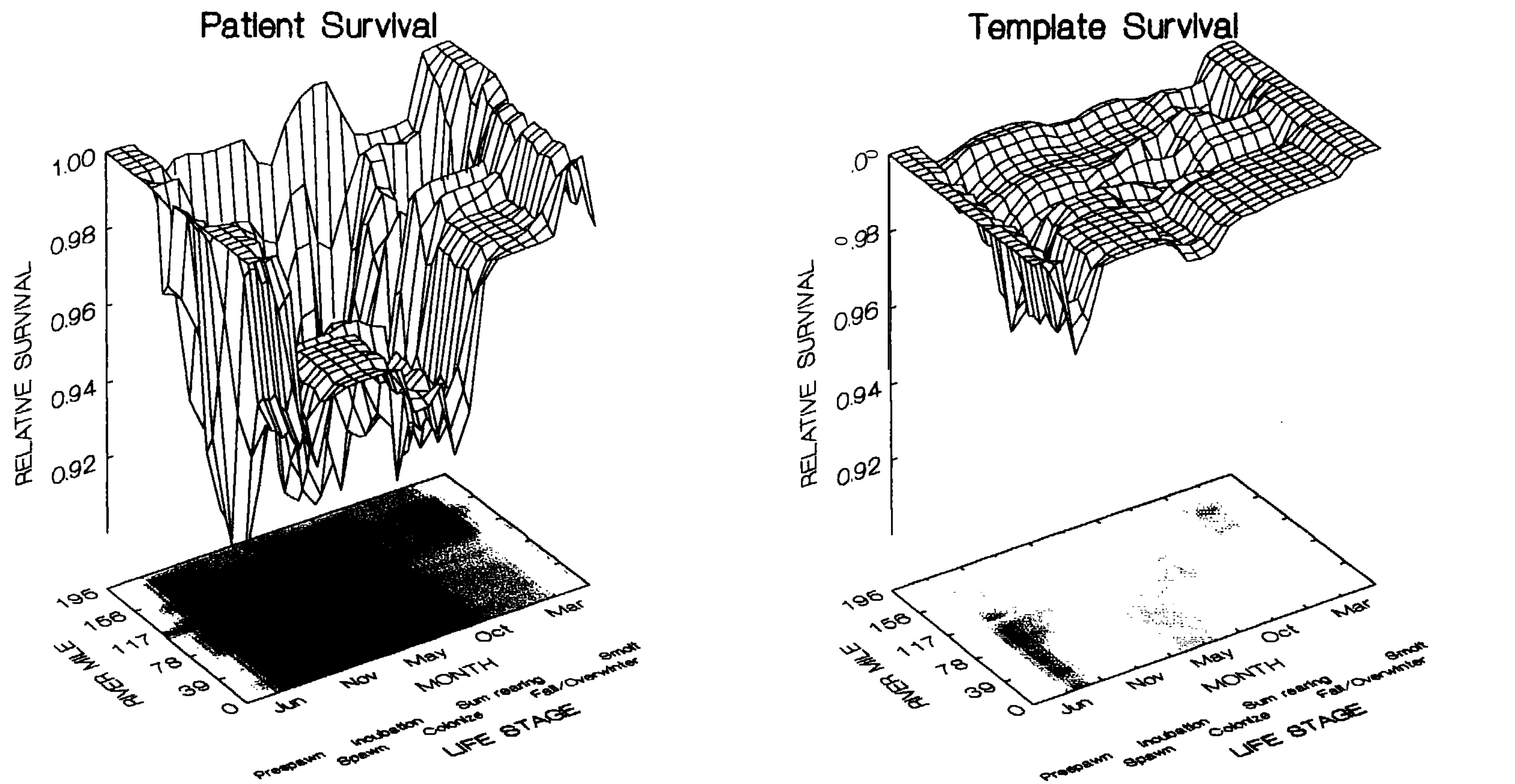


Figure 4.4. Relative productivity displayed as both three-dimensional surface plots and contour maps. These use the same data as Fig. 4.3. We etm refer these surfa as fitness landscapes.

independent survival, where a value of 1 is equivalent to the highest possible survival rate under optimal conditions in nature. From the river's mouth to the headwater reach near river mile 195, productivity appears to have declined substantially for portions or all of each life stage that occur in these waters. In general, relative productivity appears to be highest under existing conditions for adult migrants moving through the system early (April and May) and for smolts departing the system in spring of their second year of life. Productivity appears to be particularly low for Patient conditions for fry colonization, summer rearing, and overwintering in large segments of the mainstem river.

Changes in life stage-specific habitat capacity in the Grande Ronde River between Patient and Template appear to be much less dramatic than for productivity (Fig. 4.5). Still, substantial reductions are evident in some reaches for certain life stages. Capacity here is expressed as the capacity by week in fish Per channel band, where a band is the surface area of a unit of wetted channel 1 meter in length extending across the width of the channel. It is a measure of the quantity of key habitat by week within each life stage along the mainstem river. In general, habitat capacity appears to have declined most within the upper half of the river for most life stages.

Displays of productivity and capacity landscapes will vary widely between watersheds depending on their particular environmental characteristics and how they have been altered over time. An example of these differences can be seen by comparing productivity landscapes for Snow Creek coho salmon (Fig. 4.6), located in western Washington, to Grande Ronde spring chinook salmon (Fig. 4.4). Both diagnostic species have similar environmental requirements and exhibit comparable life histories in freshwater. Major changes are apparent between Patient and Template in both watersheds, though survival landscapes differ between watersheds.

The productivity and capacity landscapes are shaped by environmental attributes that exist within the same space and time dimensions that define those landscapes. Two types of displays are used to depict patterns of environmental attributes across these scales.

The first type employs the same spatial-temporal format as used for the 2-D displays of productivity and capacity. This format is used to compare broad patterns that exist for each of the 14 attributes of environmental quality (Table 4.2), all displayed on one page to facilitate comparison. The display for each attribute depicts a 2-D landscape of the attribute's effects on productivity. These graphics are meant to show only broad patterns of attribute effects, highlighting differences between reaches and life stages-they do not show differences in effects within life stages at a particular location (scoring for attributes did not distinguish effects within life stages). An example of this display is shown in Fig. 4.7 for Grande Ronde spring chinook.

The second type of graphic uses a format referred to as a "consumer report style" for comparing the relative importance of different attributes between geographic units with greater resolution than used in Fig. 4.7. This format is used for comparing conditions

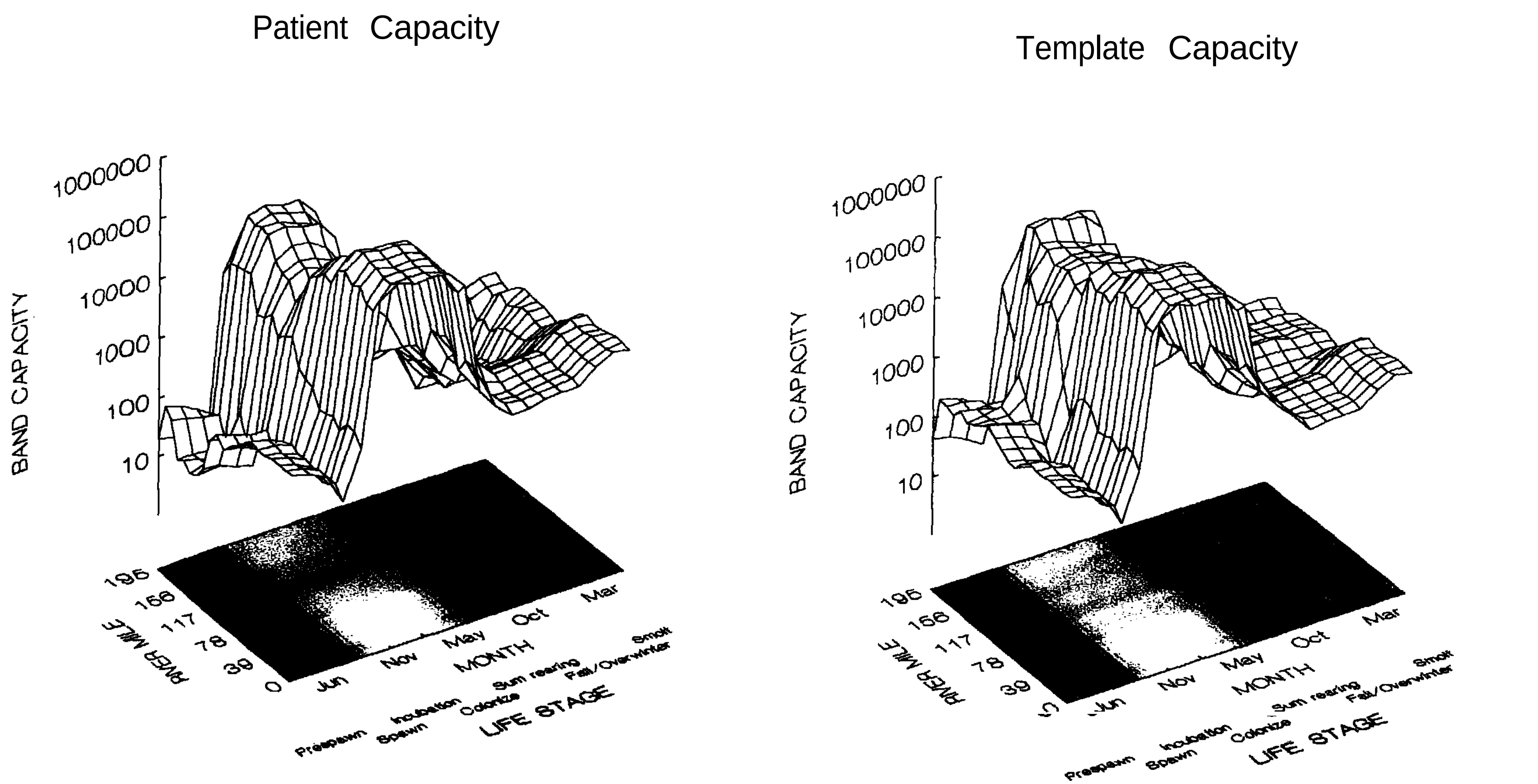


Figure 4.5 Relative capacity displayed as three-dimensional landscapes in space and time for spring chinook salmon in the mainstem Grande Ronde River. See text for definition of a habitat band

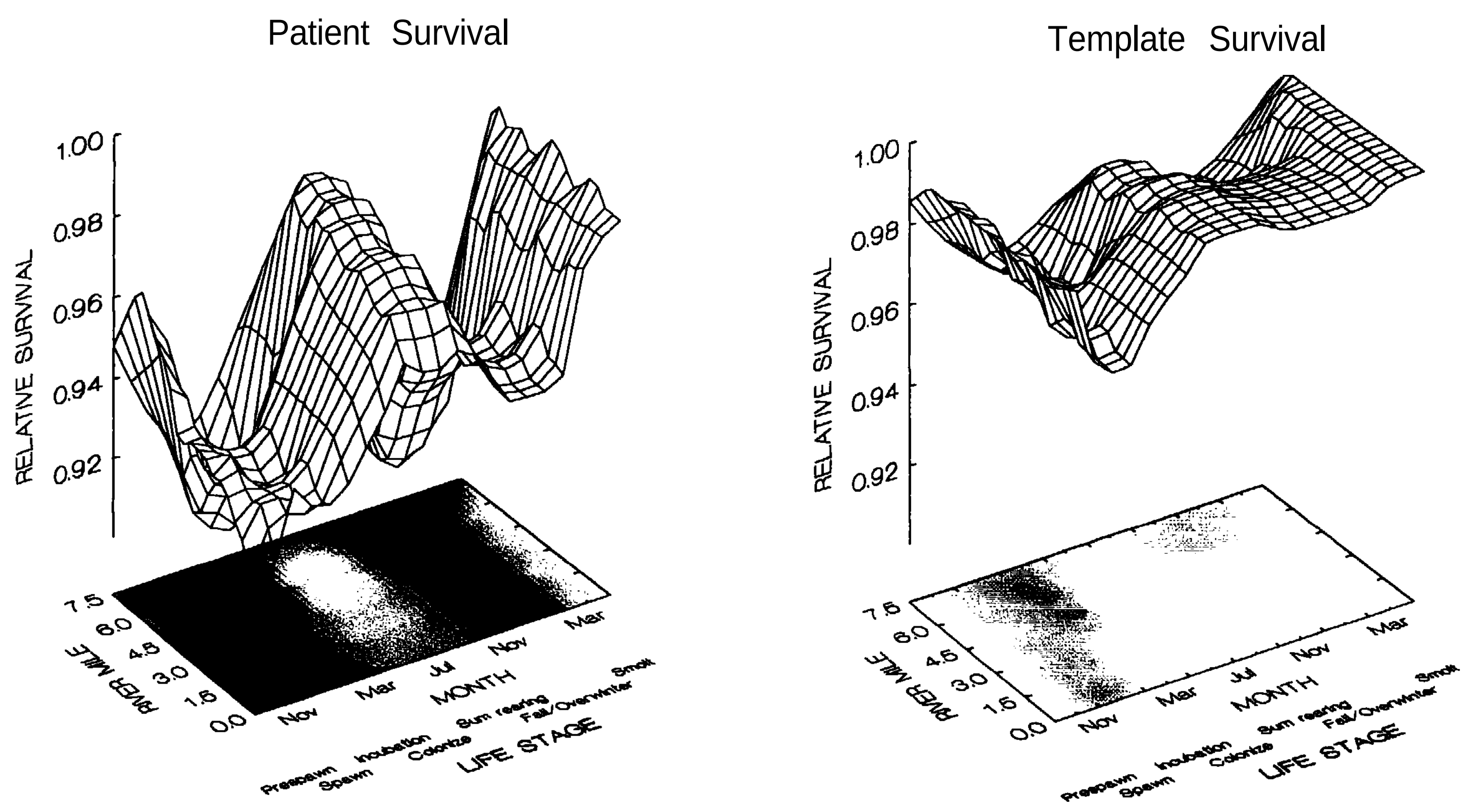


Figure 4.6. Relative productivity (density-independent survival) of coho salmon by time and location in Snow Creek, Washington. Data are displayed as both three-dimensional and contour maps.

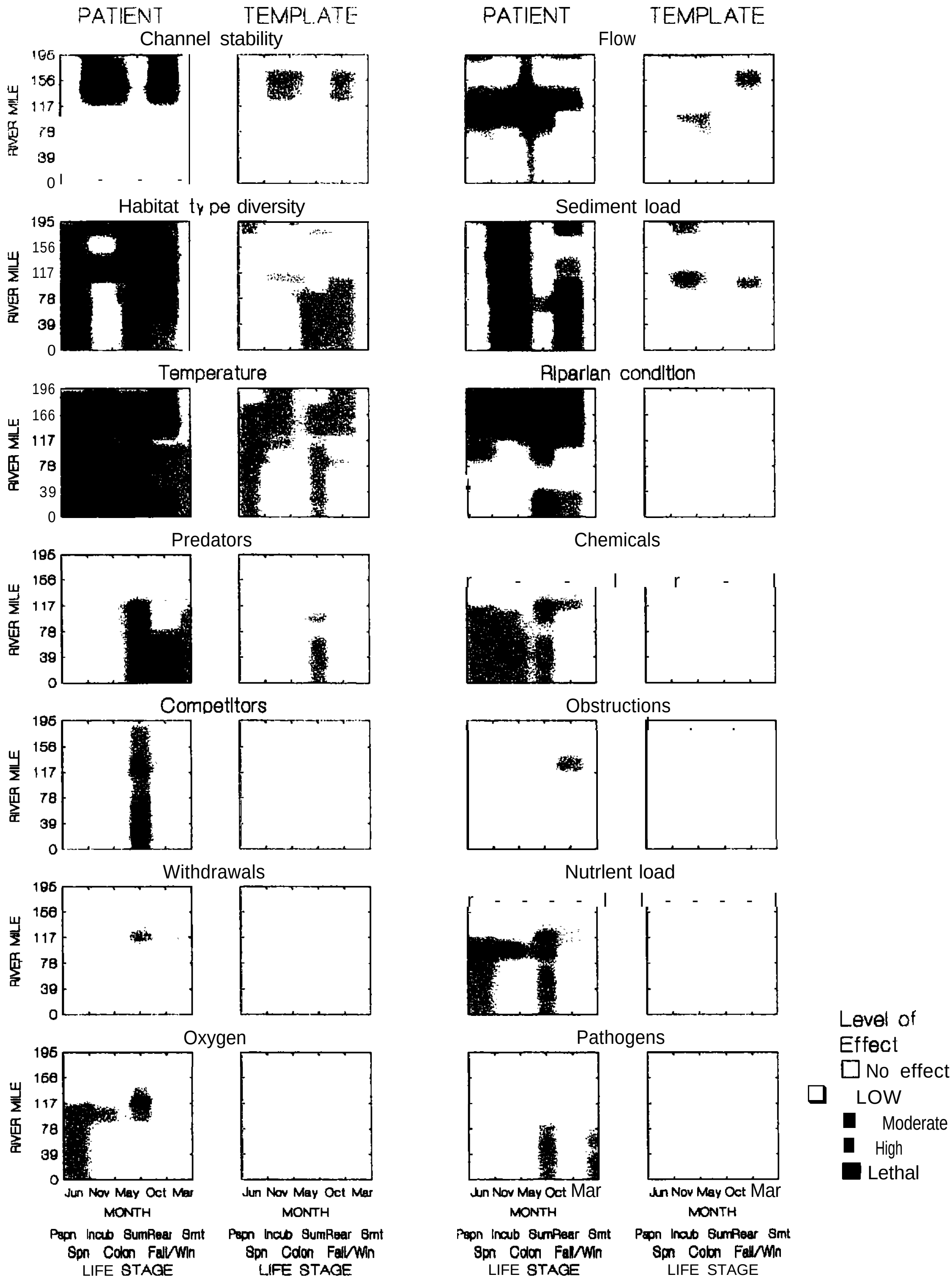


Figure 4.7. Relative effects of environmental quality attributes on spring chinook salmon productivity (density-independent survival) in the mainstem Grande Ronde River.

between mainstem river geographic units and also between tributary sub-drainages. Examples of this display are shown in Fii. 4.8 and 4.9 for two life stages of Grande Ronde spring chinook in both mainstem and tributary reaches, respectively. Circle size indicates the effects of each attribute on productivity.

Interpretive Analysis (Diagnosis)

The diagnosis is made after completing the Patient-Template Analysis. It is a determination, based on deductive analysis, of the existing potential of the diagnostic species for persistence, abundance, and distribution within the watershed. It consists of viewing and analyzing the information assembled in the PTA from a life history perspective.

The diagnosis is described in four steps: 1) definition of life history patterns and representative life history trajectories; 2) analysis of productivity profiles; 3) analysis of capacity profiles; and 4) summary determination.

Life History **Patterns** and **Representative Trajectories.** The performance-related landscapes generally define the range of conditions that can be encountered by the diagnostic species within the watershed, both in space and time. In large watersheds, there are a myriad of possible sets of conditions that different members of a population like salmon can experience over the course of life. Hence cumulative productivity and cumulative capacity for the portion of life spent within the' watershed can vary greatly for different life histories, depending on how these landscapes are traversed through space and time.

The diagnosis is conducted by use of an analytical probe. This conceptual device serves to measure indices of Performance along specific pathways, or trajectories, that members of the diagnostic species can follow through the watershed. The probe provides a means of sampling the performance-related landscapes in a manner that simulates how members of the diagnostic species might experience those conditions during the course of their lives. The diagnosis attempts to determine the relative condition of cumulative productivity and cumulative capacity for a series of life history trajectories that are biologically meaningful.

Iife history trajectories can be described consistent with general life history patterns exhibited by the diagnostic species within the environment Here a life history pattern refers to a collection of many similar trajectories, which together describe how a group of members of a diagnostic species may typically utilize the watershed through time. A single salmonid species will frequently, perhaps always, exhibit a variety of life history patterns within a largely undisturbed watershed (Reimers 1973; Schluchter and Lichatowich 1977; Carl and Healey 1984, Gharrett and Smoker 1993; and Lestelle et al. 1993a). Moreover, a set of such patterns, based on local studies or presumed to exist based on literature, can be described for the diagnostic species within the watershed. In the Grande Ronde River, for example, four generalized life history patterns for spring chinook can be described for the progeny of spawners that reproduce in a river

Mainstem River
Adult Migration and Holding Life Stage

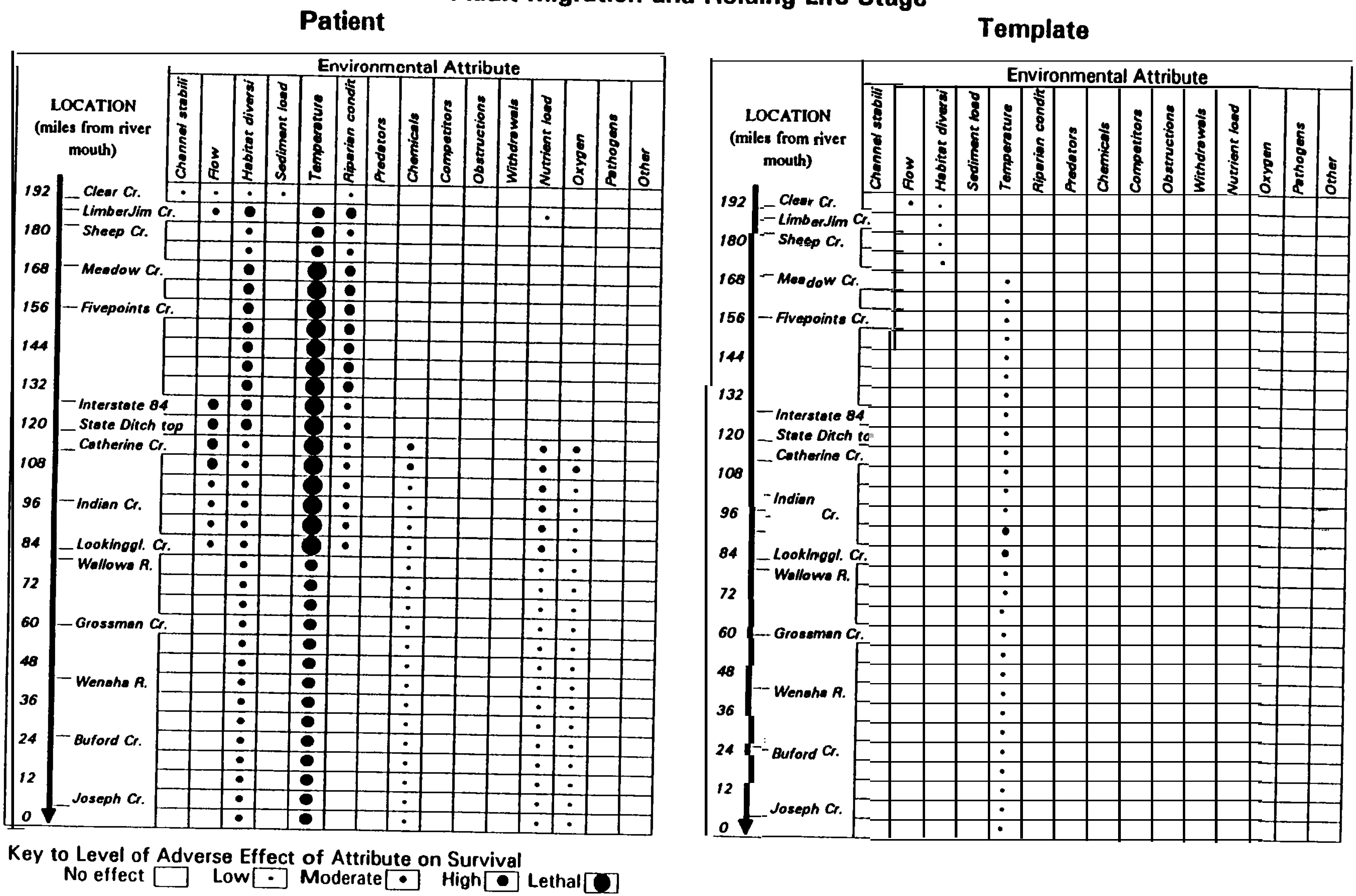
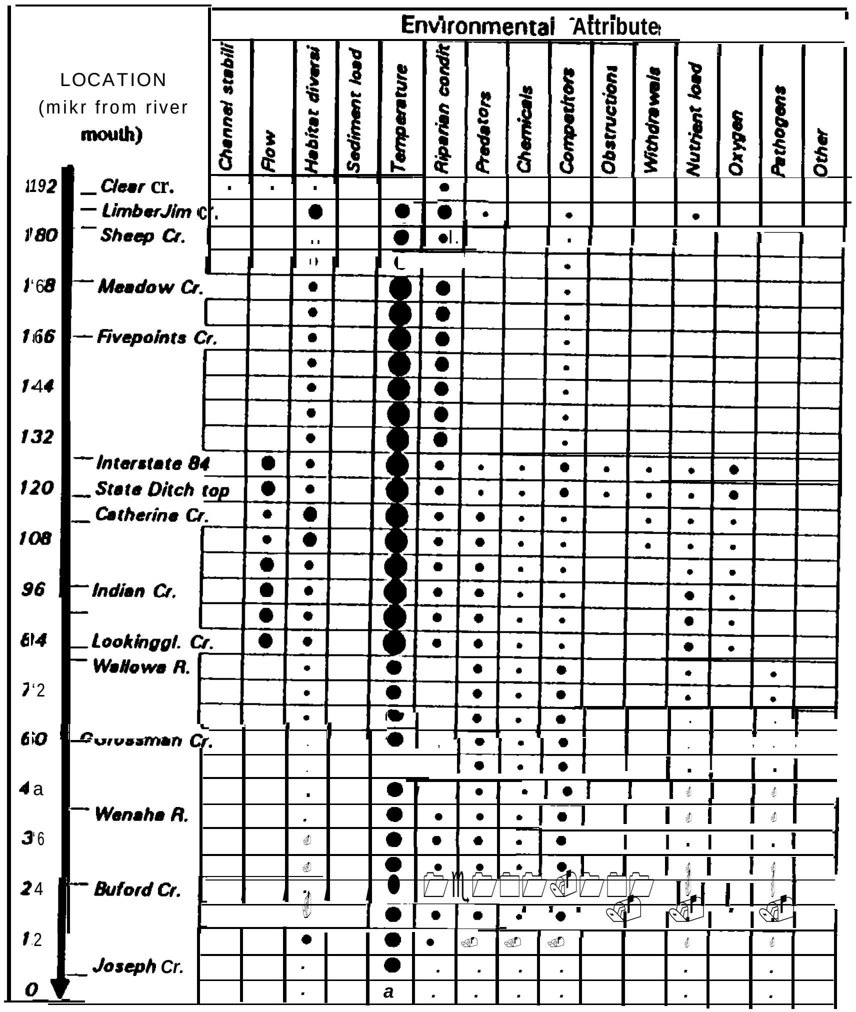
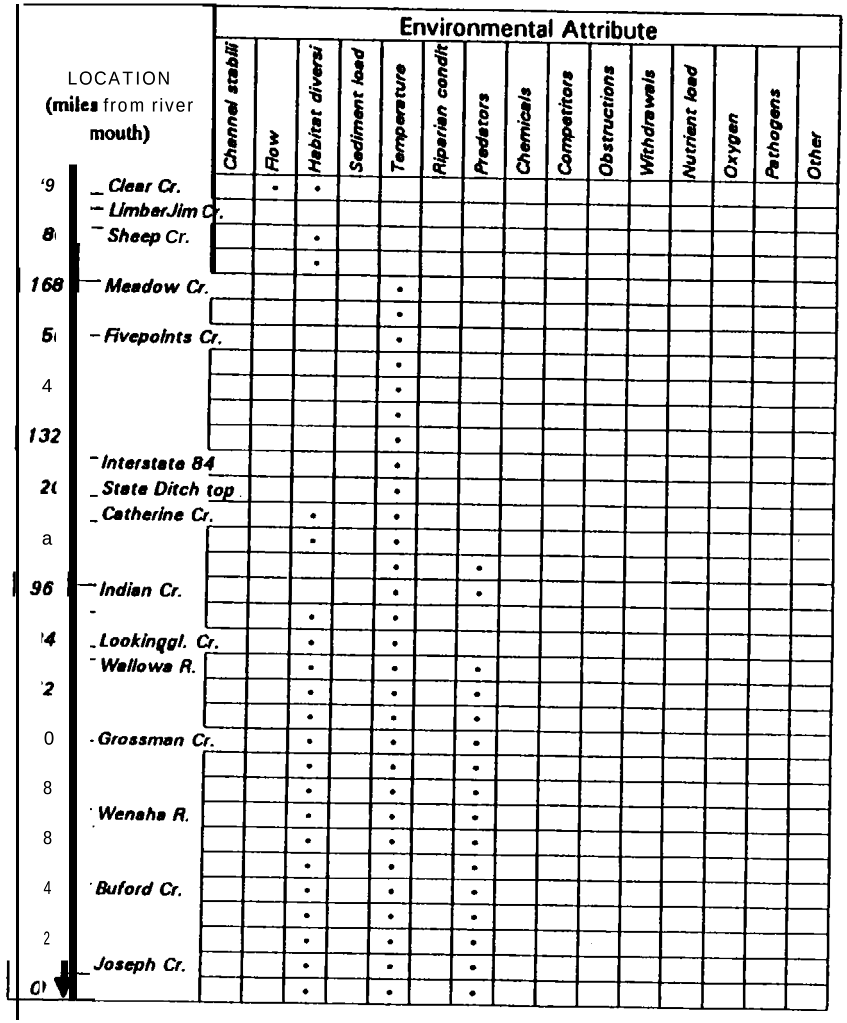


Figure 4.8(a). Life-stage specific summaries of relative effects of environmental quality attributes on spring chinook salmon productivity (density-independent survival); data shown are for prespawning adults in the mainstem Grande Ronde River.

Mainstem River
Summer Rearing Life Stage





Key to Level of Adverse Effect of Attribute on Survival
No effect [ ] Low [·] Moderate [•] High [●] Lethal [⬤]

Figure 4.8(b). Same as Fig. 4.8(a) except the data are for the summer rearing life stage.

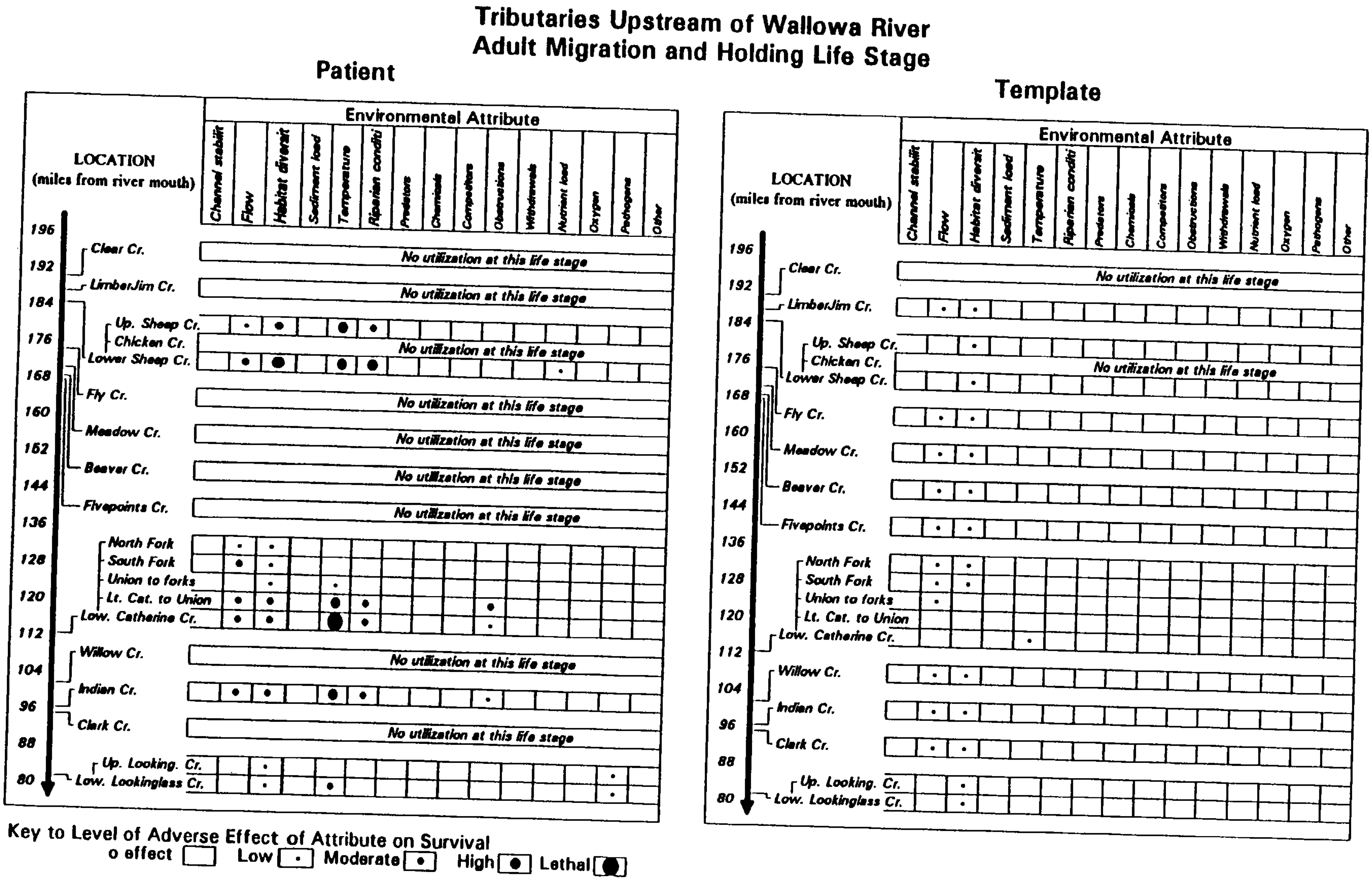


Figure 4.9(a). Life-stage specific summaries of relative effects of environmental quality attributes on spring chinook salmon productivity; data shown are for prespawning adults in tributaries to the Grande Ronde River upstream of the Wallowa River.

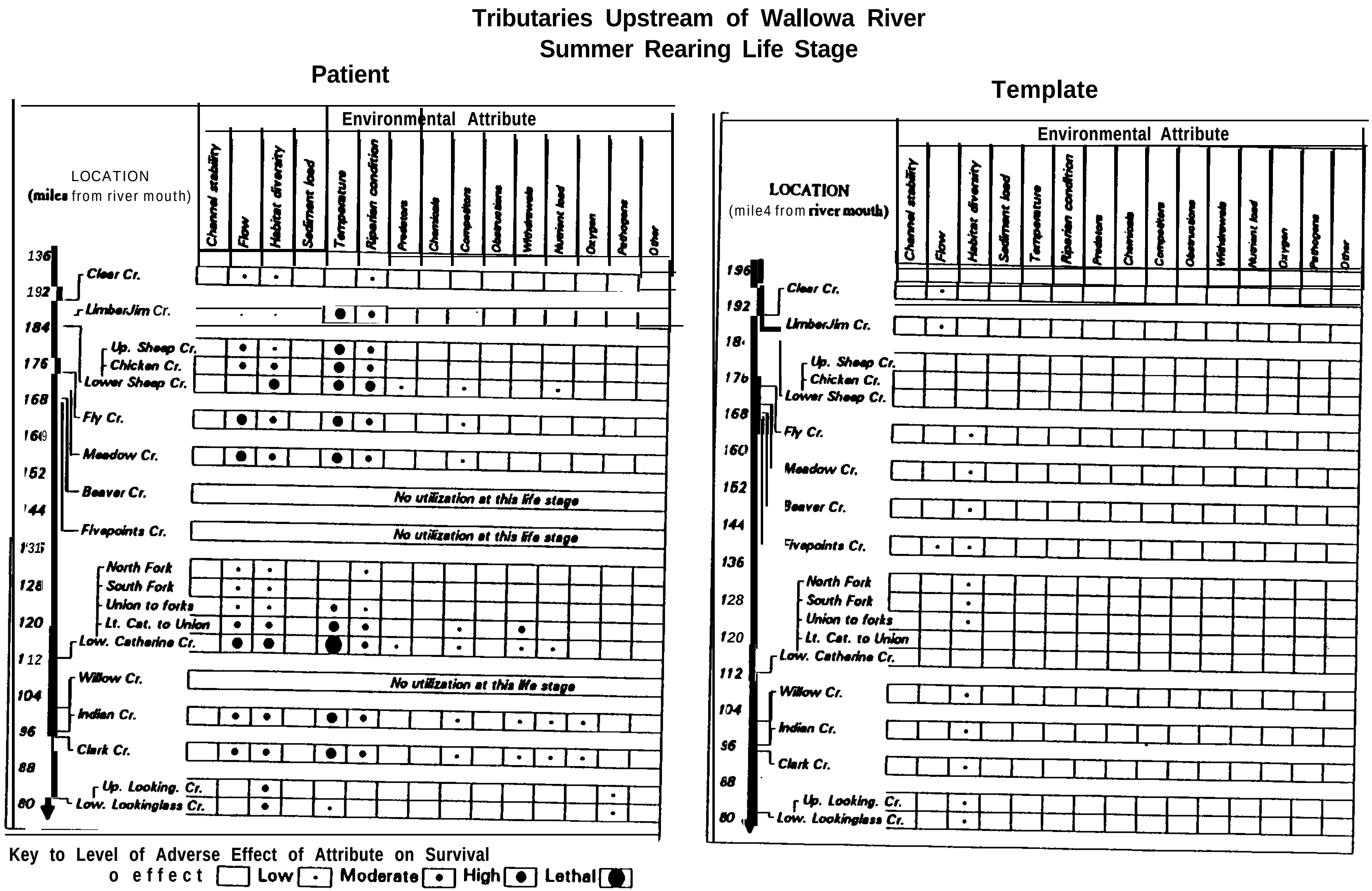


Figure 4.9(b). Same as Fig. 4.9(a) except the data are for the summer rearing life stage.

reach (Fig. 4.10). Evidence for the patterns exist from field studies in the watershed (Rich Carmichael ODFW, personal communication) or they were assumed to have been present historically (Lichatowich and Mobrand 1995).

Each of the four patterns in Fig. 4.10 is illustrated by a single representative life history trajectory. Each trajectory is shown beginning in the lower tight comer of the chart with the enay of an adult migrant salmon into the Grande Ronde River from the Snake River. The adult fish is shown entering the river in mid April. The trajectories continue upstream, charting the progress of the migrant adult to the spawning grounds in the upper river. At spawning the paths then represent progeny of the spawner, beginning as eggs and continuing through subsequent life stages until seaward migration as smolts.

The four patterns differ in how juveniles utilize the watershed Pattern 1 is the primary life history pattern that exists within the upper river today, progeny of spawners using the upper river are believed to rear in the general vicinity of spawning. Pattern 2 characterizes a secondary life history pattern that exists today, representing juvenile fish that migrate a considerable distance downstream in fall for overwintering. Pattern 3 represents juvenile progeny that migrate downstream immediately following fry emergence from spawning gravels; rearing occurs some distance downstream of the natal site. Pat-tern 4 represents juvenile progeny that behave similarly to those shown for Pattern 3, but these then emigrate from the river in fall, possibly as seaward migrating smolts.

The singIe trajectories shown in each frame of Fig. 4.10 are samples of the four general life history patterns discussed above. One or more representative trajectories can be used to analyze performance of each life history pattern.

This analytical device is one of the most significant aspects of the EDT diagnostic approach. It facilitates analysis of performance across the watershed and provides the means for linking all other life stages that occur outside that drainage. In doing so, a comparison can be made of potential persistence and abundance where life histories are brought to closure at reproduction. Factors affecting mortality along the full life cycle can then be identified and analyzed, enabling cumulative effects of these factors to be assessed.

Productivity Profiles. Once trajectories representative of a set of life history patterns have been described, performance profiles can be constructed and associated performance indices computed A performance profile shows the specific pattern of relative productivity or capacity by week of life along a life history trajectory. These weekly values allow the computation of both the cumulative productivity index and the cumulative capacity index for each trajectory. Index values can be computed for both Patient and Template for each trajectory.

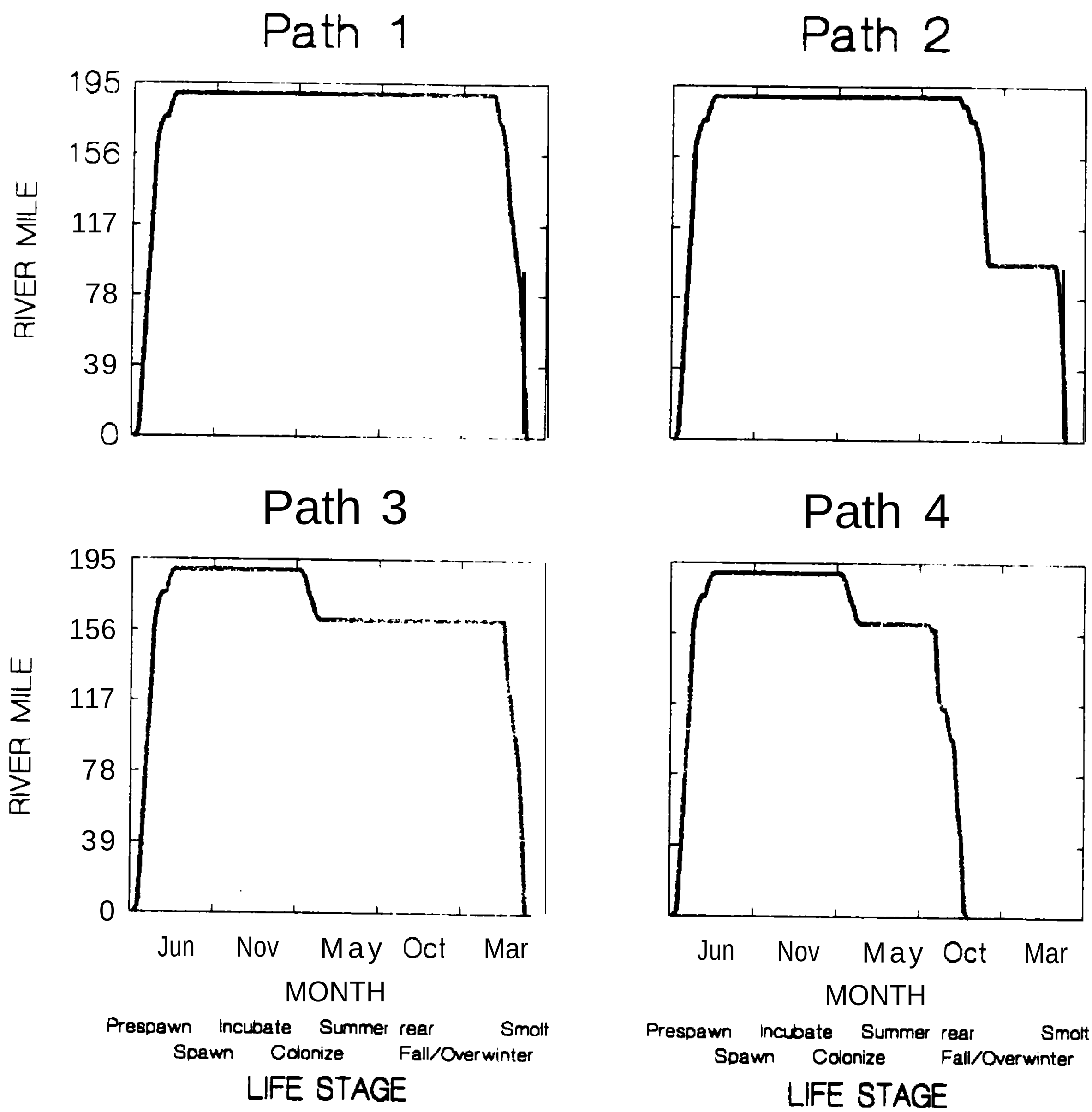


Figure 4.10. Four generalized life history patterns **of spring chinook salmon in the Grande Ronde River, as illustratd by sample life history trajectories.**

CHAPTER
P About this Primer
1 About EDT
2 About Tasks
3 About Theory
4 About Tools
Diagnostic Tools
Descriptive Analysis(PTA)
Interpretive Analysis
Life history diversity
Productivity
Capacity
Synthesis
Treatment Identification Tools
Benefit and Risk Analysis Tools
Monitoring Tools

The simplest index to compute is the cumulative productivity index, which is a measure of the overall productivity for the entire life history trajectory. Computation of the measure is based on an extension of Equation (1) incorporating the relative productivity values obtained in the workshops.

A productivity (p) value is estimated for each life stage i contained within the trajectory as follows:

$$p_i = \prod_{j=1}^{m} (MaxProd_j \times RelProd_j) \qquad (7)$$

where $MaxProd_j$ is the productivity of the diagnostic species under optimal environmental conditions in weekj of life stage i and $RelProd_j$ is the relative productivity value estimated for the species in the stream reach of interest in week j of life stage i.

The relative productivity ($RelProd$) use for any life stage i can be disaggregated into values for each weekj of the life stage, as described earlier under the section "Relative Productivity."

$MaxProd$ for any life stage i is the theoretical maximum productivity value for that life stage which would occur under optimal environmental conditions. We approximated the survival portion of the maximum productivities for freshwater life stages of spring chinook and coho salmon based on a review of field studies and discussions with individuals knowledgeable **about survivals** during specific life stages (Bjomn 1978; Jonasson and Lindsay 1988; Lestelle et al. 1993b; ODFW unpublished data; Ted Bjornn personal communication; Phil Peterson personal communication). These are listed in Table 4.6. The value of $MaxProd$ in life stage i can then be disaggregated into weekly values for each week j of the life stage, using Equation *(4).* Average sex ratios of spawners and fecundity per female spawner can be approximated similarly and incorporated into the productivity value for the weekly value of $MaxProd$ when spawning occurs. These types of estimates can be derived for various diagnostic species.

The path of the trajectory determines what values of $RelProd_j$ are used in computing p_i. Each stream reach may have its own unique set of $RelProd_j$ values. When more than one reach is crossed by a trajectory within any weekj, then the weighted mean value is used, where weighting is based on the number of stream miles associated with each value of $RelProd_j$.

Once values of p are computed for each life stage i, the cumulative productivity index (PI_n) for the entire trajectory is easily computed f'rom Equation (l), where PI,, = P_n.

Table 4.6. Estimates of maximum life stage-specific productivity (density-mdependent survival) for freshwater life stages and corresponding cumulative productivity of coho and spring chinook salmon. These values would be expected under optimal environmental conditions; see text.

Life stage	Coho	Spring chinook
Pre-spawning adults	1.00	0.95
Spawning	1.00	1.00
Incubation	0.70	0.70
Fry colonization	0.70	0.80
Summer rearing	0.75	0.70
Overwintering	0.75	0.75
Smolt to smolt	0.95	0.95
Cumulative productivity	0.26	0.27

Results of applying this procedure are illustrated in Fii. 4.11 for the trajectories representing the four generalized life history patterns for Grande Ronde spring chinook. The productivity profile associated with each trajectory is shown, both for Patient and Template, as well as the respective computed value of the cumulative productivity index. In this example, the index suggests that cumulative productivity has declined sharply over the past century for all four life history patterns associated with a group of fish spawning in the upper Grande Ronde River. Index values expressed as smolts per spawner for the four sample life history trajectories ranged between O-185 and 502-862 for Patient and Template, respectively (Fig. 4.11). The performance profiles allow us to more carefully examine the differences between Patient and Template productivities along the trajectory. The profile compares relative productivity of the Patient and Template.

The productivity index values for different life histories within the watershed can be combined with smolt to adult survival rates to assess cumulative productivity across the entire life cycle. This should be done by extending the Patient-Template Analysis to the full life cycle, then computing cumulative productivity index values for the full life. Index values that exceed 1 over a full life cycle would be expected to persist

The utility of making this examination is illustrated using the four life history patterns for Grande Ronde River spring chinook described earlier. Smolt to adult survival rates are assumed to vary from less than 0.5% to 2% for Grande Ronde spring chinook (Cramer and Neeley 1993), averaging about 1%. Applying this rate to the trajectory associated with life history **pattern** 1 for the Patient (Fig. 4.10), for example, would mean that approximately 1.8 progeny adults would return to the river per parent spawner (185 smolts per adult *x* 0.01 returning adults per smolt) in the absence of population density effects. This trajectory could be expected to be sustainable if all of these values held constant In comparison, cumulative productivity index values associated with trajectories representing life history patterns 2-4, suggest that these patterns are not currently sustainable because index values over the full life are less than

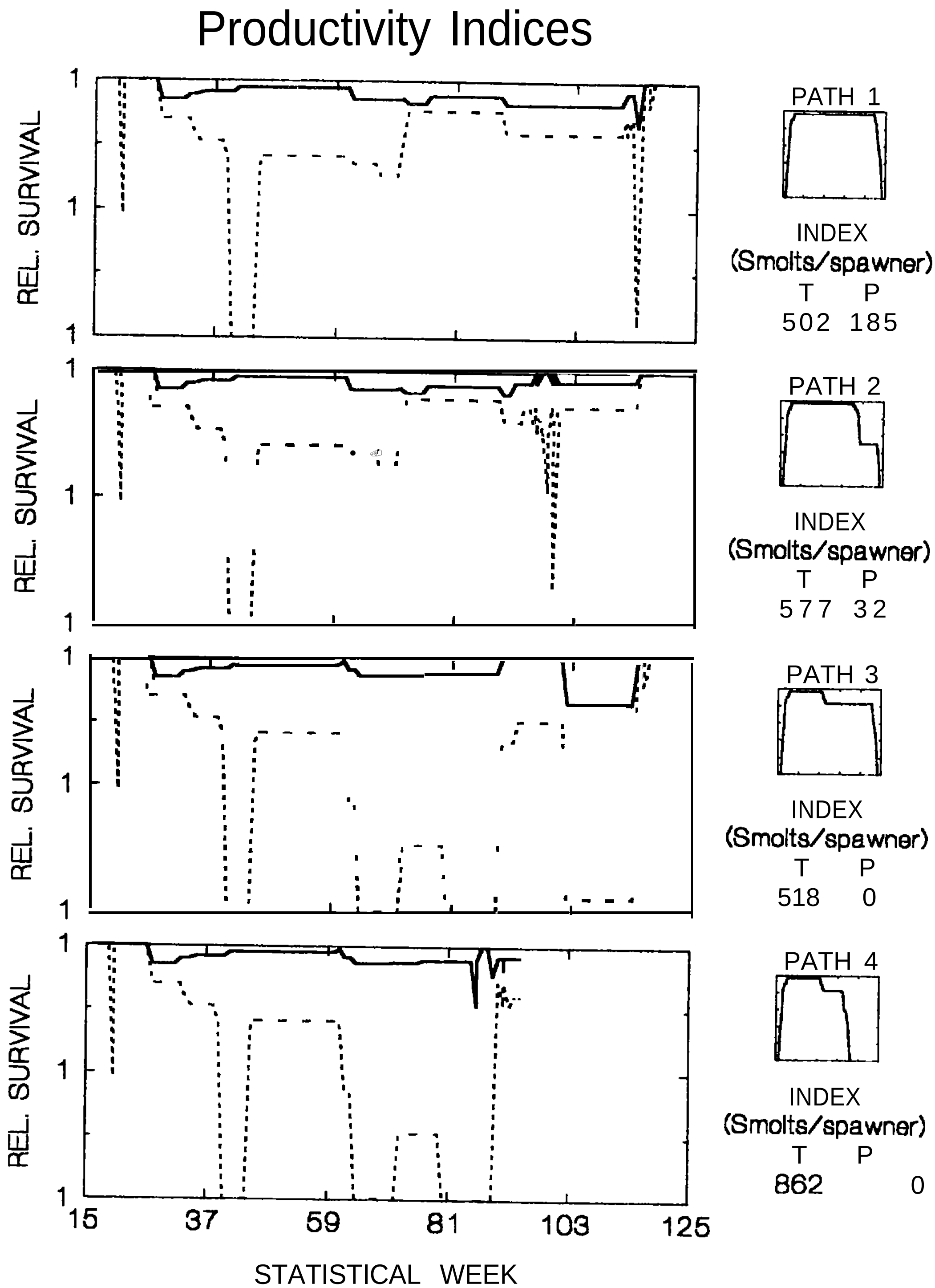


Figure 4.11. Productivity indices (density-independent survival) for four life history trajectories (paths 1-4) of Grande Ronde spring chinook salmon. Relative productivity profiles are shown on left (weekly values). Cumulative productivity indices are listed on the right.

1. On the other hand, smolt to adult survival rates would have been much higher in the Template which, when applied to the higher productivities within the Grande Ronde basin, would have resulted in very high cumulative productivity values for the full life histories.

It may be useful to consider the relationship between cumulative productivity for the segment of life history within a watershed to that found outside the watershed (Fig. 4.12). Cumulative productivity values for each area are shown along the Y and X axes, respectively. The curved line passing through the figure can be thought of as the margin of sustainability for any given life history pattern (or trajectory). The line represents a progeny per parent ratio (adult returns per spawner) of 1; i.e., where the number of parent spawners is exactly replaced by its returning progeny. Values above the curve show combinations of productivities that will sustain a life history; those below the curve lead to extinction.

Present day freshwater productivities and smolt to adult survival rates are depicted for Grande Ronde spring chinook in Fig. 4.12 for illustration purposes. These rates are shown reduced from historic levels. These reductions combine such that cumulative productivity across the entire life cycle is often less than one returning adult per parent spawner. Only those life histories with the highest productivities within the watershed appear to be currently sustainable and then only at the higher end of the range for smolt to adult survival.

Capacity Profiles. This step involves constructing capacity profiles associated with each life history trajectory and computing the corresponding cumulative capacity index values. Recall that capacity here is expressed as the capacity by week in fish per channel band, where a band is the surface area of a unit of wetted channel having a length of 1 m and extending across the width of the channel. It is a measure of the quantity of key habitat that exists in each week along the length of a trajectory. The cumulative capacity index is a measure of the cumulative capacity over the entire length of the trajectory, which takes into account weekly capacity values as well as weekly productivities, consistent with Equations (2) and (3).

The computation of weekly capacity values for all life stages is based on an estimation of the capacity of a square meter of key habitat for any week within each life stage for a stream having optimal environmental quality in all stages. This enables us to compute the maximum potential density for a unit of habitat quantity in a way that removes the effect of environmental quality. These estimates of weekly capacity of a square meter of key habitat (maximum density) can then be used for any stream, despite differences in environmental quality (a possible adjustment to these values is described near the end of this section).

The estimation procedure for maximum potential density (MaxDen) for a square meter of key habitat in any week m for any life stage i in a stream with optimal environmental

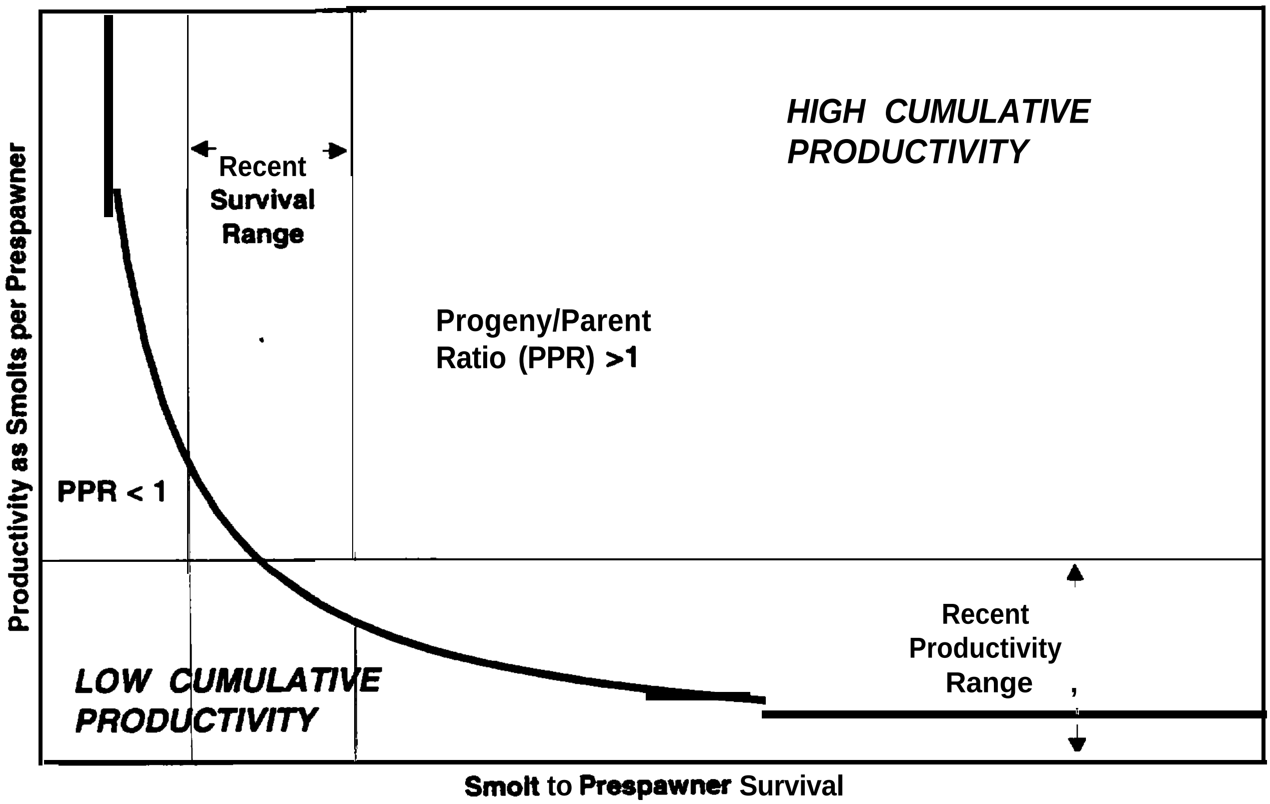


Figure 4.12. Representation of the relationship between productivities of life stages within the Grande Ronde Basin and outside the basin. The curved line represents a cumulative productivity (PPR) of one. The PPR must exceed one to sustain the life history pattern. The present day productivity range is shown as the shaded area in the graph

quality can be derived from Equation (5), here expressed as

$$MaxDen_i = \frac{P_i}{\sum_{j=1}^{m} \frac{P_j}{MaxDen_j}} \tag{8}$$

where P_i is the cumulative productivity for m weeks under optimal conditions and $MaxDen_i$ is the cumulative maximum density for m weeks. For spring chinook and coho salmon P_i is simply equal to the cumulative productivity values given in Table 4.6. It is assumed that the cumulative maximum density at the end of any life stage i is known from studies (Nickelson et al. 1993) or can be inferred from those studies, and further, thatthemaxim urn density in key habitat in week m-l is simply

$$MaxDen_{m-1} = MaxDen_m \times WeekScalar \tag{9}$$

where *WeekScalar* is a scalar that adjusts upward the maximum possible density in a week having younger, hence smaller, fish compared to the following week As fish grow they require a greater amount of food and space, thus the maximum possible density in the last week of a life stage will be the smallest of any week in the stage. It is assumed that the weekly scalar is constant for all weeks in a life stage, and that scalars are known or can be inferred for each life stage.

The maximum density in the last week of a life stage (week m) in a stream under optimal conditions can then be derived using Equations (8) and (9), resulting in the following:

$$MaxDen_m = \frac{\left(\sum_{j=1}^{m} \frac{P_j}{WeekScalar^{j-1}} \right) \times MaxDen_i}{P_i} \tag{10}$$

where P_i is the cumulative productivity for m weeks. Once the maximum density value is computed for the last week and given scalars for each life stage, then maximum density values can be easily computed for all weeks within each life stage with Equation (9).

Estimates of cumulative maximum densities for key habitat by life stage have been reported by Nickelson et al. (1993) for coho salmon (Table 4.7); we assume that these values are good approximations of values for spring chinook salmon. Table 4.7 provides estimates of scalars by life stage that we have used in previous analyses.

Estimates of weekly maximum densities in key habitat for a stream having optimal environmental quality were then computed using Equations (9) and (10) using a standardized number of weeks for each life stage ('Table 4.7). This gives the means of computing the maximum densities for the first week in each life stage, which becomes

Table 4.7. Estimates of cumulative maximum densities (fish/m²) of coho salmon within key (preferred) habitat under optimal environmental conditions and weekly scalars used in estimating weekly densities within each life stage; see text. Density values are assumed to be generally representative of streams within the middle of the range of the naturally occurring nutrient base (as related to the production of food resources).

Life stage	Maximum density (fish/m^2)	Weekly scalar
Pre-spawning adults	1.00	1.00
Spawning	0.22	1.00
Incubation	400.00	1.04
Fry colonization	5.75	1.04
Summer rearing	1.65	1.04
Overwintering	1.85	1.02
Smolt to smolt	1.00	1.05

the basis of computing weekly capacities for all life stages in any stream reach where the number of weeks per stage may vary.

Once these values are estimated for all stream reaches, the cumulative capacity index can be computed for any life history trajectory using the appropriate weekly values of maximum density and using Equations (5) and (6) and corresponding weekly values of productivity as described earlier in Step 2 (Chapter 3, EDT Framework). An example of applying this procedure is illustrated for the four representative life history trajectories for Grande Ronde spring chinook in Fig. 4.13. 'The capacity profile associated with each trajectory is shown, both for Patient and Template, as well as the respective computed values of the cumulative capacity index. Note that the Y-axis for the chart showing capacity profiles uses a log scale. It is important to note in Fig. 4.13 that the capacity profiles differ from the cumulative capacity indices. Habitat capacities within weekly intervals are largely unchanged between Template and Patient over large segments of the trajectories. Only minor differences exist for trajectory path 1. Cumulative capacities, which incorporate productivities as well as life-stage specific capacities, are significantly changed for all paths. These index values show that the capability of the watershed to produce natural salmon smolt has been severely reduced.

It should be noted that this procedure allows for a second scaling factor to be introduced to account for significant differences that might exist in food production between streams. Streams that are nuaient rich or high in alkalinity can support higher maximum densities of animals compared to less productive streams. A scalar can be used to adjust the cumulative capacity values listed in Table 4.7 to reflect such differences.

Synthesis. The final step in the diagnosis consists of making a summary determination of the general condition of the diagnostic species and the relative contributions of factors affecting the species. The determination is made within the context of program

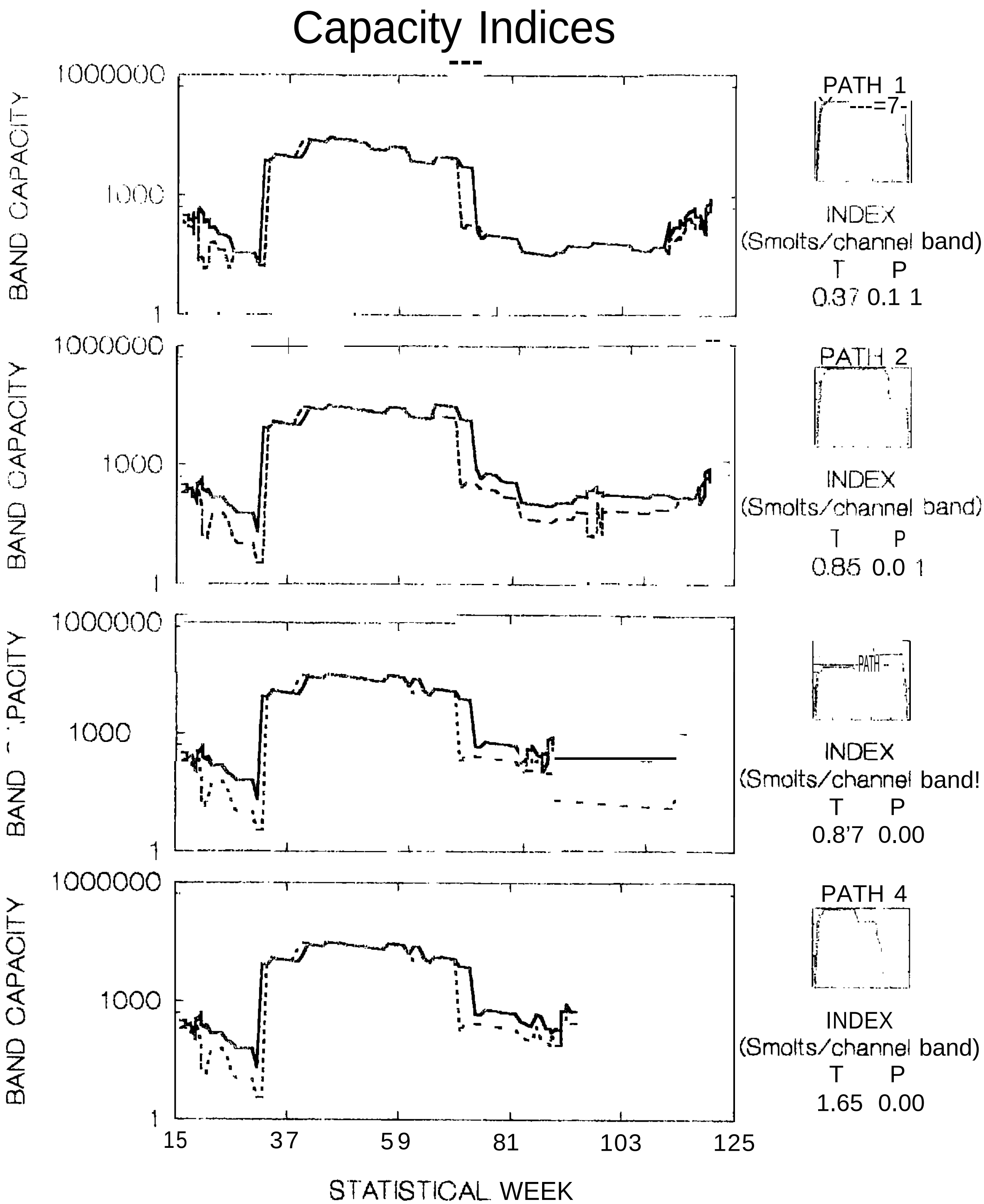


Figure 4.13. Capacity indices for four life history trajectories (paths 1-4) of Grande Ronde spring chinook salmon. Capacity profiles are shown on left, where capacity is expressed as weekly values of fish per channel band (log scale). Cumulative capacity indices are listed on the right.

objectives. Large amounts of information must first be viewed-at small scales defined by individual trajectories and at much larger scales that show broad patterns across the landscape.

The summary determination involves integration of all the information across these scales into clear concise statements that summarize the diagnosis. These summary statements, combined with key visual displays, are the basis of communicating the diagnosis to decision makers. The determination describes the condition of health in terms of the potential for persistence, abundance, and distribution, as well as a disclosure of the apparent factors contributing to that condition.

It may be useful, even necessary, to formulate more than one plausible diagnosis to help identify information needs for future work

Treatment Identification Tools

The purpose of the treatment identification step in the planning process is to assemble a collection of candidate actions. Because proposed actions can come from many sources (from individuals, organizations, and agencies) a procedure needs to be followed that assures inclusion of alternatives based upon the diagnosis.

A procedure for identifying actions consistent with the diagnosis involves first formulating one or more basin-wide strategies. A strategy gives overall direction for guiding the development of watershed improvement actions. Strategies aimed at ecosystem management need to be consistent with principles of watershed dynamics, ecosystem function, and conservation biology. These principles can be simply captured in one general principle that incorporates a life history perspective for the diagnostic species.

In simplest terms, the principle calls for setting the following priorities: first, maintaining, second, improving, and third, restoring. The condition (or health) of existing life history patterns for the diagnostic species are the criteria for establishing strategic priorities. The rationale for this principle is that it is prudent to maintain and make secure existing life history patterns before attempting to replenish or restore patterns that have been disrupted through past changes to the watershed.

Also, it becomes evident once the concepts of performance are grasped that it is generally more advantageous to focus on factors affecting productivity (i.e., environmental quality) than on life stage specific habitat quantities (i.e., capacity). Improvements in productivity have a dual benefit They increase cumulative productivity, hence the resilience of life history patterns. They also increase cumulative capacity. Recall that cumulative capacity is comprised of both life stage specific productivities and capacities, see Equation (2). Although priorities described below identify environmental quality and quantity issues together, quality should generally be considered to be of higher priority than quantity.

This general principle places highest Priority on *maintaining* the existing quality and quantity of habitat associated with the primary, or most productive, life history patterns remaining today (Table 4.8; illustrated for the Grande Ronde example in Fig. 4.14). These life history patterns are the dominant pathways in space and time still being used and, therefore, provide the most resilience to the Population to protect it from mortality pressures anywhere in the life cycle. Maintenance of these life history patterns is vital to safeguarding the Population from further decline.

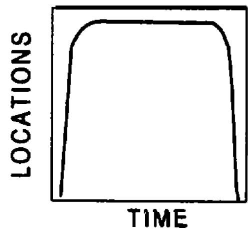
Table 4.8. Strategic priorities for watershed improvement actions based on a life history perspective for diagnostic species.

Priority	Description
1	Maintain habitat quality associated with the primary, or most productive, life history patterns, including migration corridors.
2	Improve habitat quality associated with the primary life history patterns, including migration corridors.
3	Maintain habitat quality associated with secondary life history patterns, including migration corridors.
4	Improve habitat quality associated with secondary life history patterns, including migration corridors.
5	Improve habitat quality in other areas to begin restoring other life history patterns.
6	Reconnect habitat segments to restore connectivity for other life history patterns.

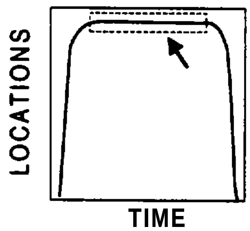
The second priority reinforces the first; it calls for *improving* the quality and quantity of habitat associated with the primary life history patterns remaining today (Table 4.8; Fig. 4.14). In doing so, the cumulative productivity and cumulative capacity of these patterns can be increased. Resilience of these patterns would thereby be strengthened, improving the chances that they can be sustained under today's prevailing environmental conditions. Particular attention should be given to areas that are used for longer Portions of the life history; improvements in survival through these areas will result in the largest overall improvement in cumulative productivity.

Priorities three and four are similar to the first two, except that secondary life history patterns are targeted for attention (Table 4.8; Fig. 4.14). Secondary patterns are those that are still utilized by the Population but where survival conditions along the pathways are marginal. These strategic priorities would maintain, then improve, conditions along the space-time corridors associated with these patterns.

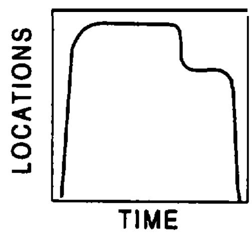
Priorities five and six call for efforts to *begin restoring* life history Patterns that have been lost to the Population (Table 4.8; Fig. 4.14). The rationale for placing restoration of lost patterns at a lower priority level is that it is likely that more extensive and longer-term actions will be required in this case. Moreover, reconnection of habitat segments associated with lost life history Patterns should not be made until there is a high chance



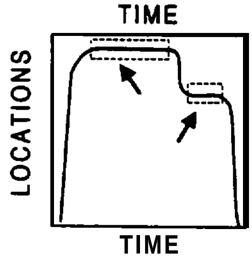
PRIORITY ONE
Maintain the quality of habitat associated with the primary life history pattern, including migration corridors.



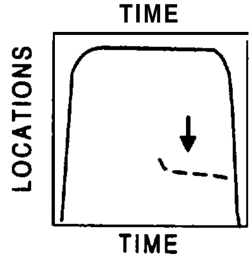
PRIORITY TWO
Improve the quality of habitat associated with the primary life history pattern, with particular attention to areas used for longer portions of the life history.



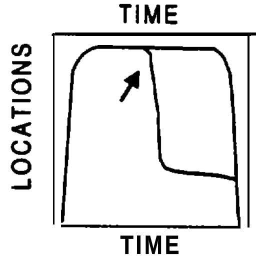
PRIORITY THREE
Maintain the quality of habitat associated with the secondary life history pattern, including migration corridors.



PRIORITY FOUR
Improve the quality of habitat associated with the secondary life history pattern, with particular attention to areas used for longer portions of the life history.



PRIORITY FIVE
Improve habitat quality in other areas to begin restoring additional life history patterns.



PRIORITY SIX
Reconnect habitat segments to restore additional life history patterns.

Figure 4.14. Example of strategic priorities for restoration derived from a diagnosis of spring chinook salmon in the upper Grande Ronde River.

that fish following such pathways can realistically achieve closure to their life cycle. Otherwise, partially connected pathways can act as drains to population productivity.

These strategic priorities are arranged to focus efforts where they are likely to achieve the most benefit The priorities recognize, however, that watershed improvement efforts need a long-term vision. Success at all six priority levels may be required to achieve sustainable goals for the watershed over a long time period. The priorities should not be viewed rigidly-the first- priority need not be achieved before progressing to the next Opportunities, for example, may become available to improve conditions associated with a secondary life stage that would require little expenditure of resources. Cost of actions is clearly a necessary consideration.

The strategic priorities provide a basis for establishing guidelines to identify effective actions. In considering a possible action, careful consideration should be given to response time for the action, technical feasibility, and whether it can be implemented without negative side effects. Examples of actions aimed at affecting either productivity or capacity are described in Appendix B. The examples are shown for coho salmon but similar actions would apply to other species of stream rearing salmonids.

Benefit and Risk Analysis Tools

Following identification of candidate actions, an analysis of trade-offs is performed to compare expected benefits and risks of individual, or suites, of actions. The analysis requires an understanding of values and objectives for the watershed.

Risk here refers to the possible outcomes of the candidate actions in terms of stakeholder values and objectives (note that risks of no action should always be included). There needs to be consideration of both the possibility of increased values (benefits) and reduced values (i.e. the event where values/objectives are not fully met). The nature and extent of these potential consequences, and the likelihood of their occurrence, are implied when risk is considered here.

A key to understanding risk is the implied cause and effect relationship between actions and stakeholder values. This relationship is made explicit when the specific assumptions in this linkage are stated. Hence the very first step in the benefit-risk analysis is an identification of all action specific assumptions. Once these are identified, we can analyze the uncertainties associated with all assumptions needed to form the logical conclusion that the action will lead to achievement of a specified set of objectives without adverse impact on other values.

Identifying Assumptions

Assumptions are logical statements about presumed relationships and conditions of the ecosystem and its function. They are always present in the management of natural resources because knowledge is imperfect The assumptions need to be stated explicitly to enable those engaged in the management process, or the general public, to consider them and use them as a basis for learning and improving future decision making. They also need to be explicitly disclosed to enable questioning. For example: Are the assumptions reasonable, i.e. are they consistent with existing information? Do the assumptions pose significant risk? Can the assumptions be tested?

The process of identified and disclosed assumptions associated with each candidate action helps provide accountability to the overall planning process itself and to the public in considering potential benefits and risks of those proposed actions. It is a step that is essential if adaptive management is to become a reality.

There are five categories of assumptions associated with the planning process and with the conceptual framework (see Fig. 3.3). These categories are:

1. *Actions* to *attributes*: These assumptions refer to the relationship between actions and their impact on environmental conditions or attributes.

2 *Attributes to performance*: *These* assumptions involve the effects of environmental attributes on the elements of biological performance, i.e., on productivity, capacity and life history diversity.

3. *Performance to objectives*: These assumptions refer to the relationship between biological performance and stakeholder values or program objectives.

4. *Concep tual framework*: These assumptions involve conceptual or theoretical bases for understanding the ecosystem and its processes.

5. *Monitoring* **and** *evaluation* *(M&E)*: *These* assumptions involve our ability to monitor and evaluate changes in the ecosystem; i.e., the feasibility to make observations from which conclusions **can be drawn about the validity** of the other categories of assumptions.

The planning process described in Chapter 2 requires the identificaaon of all of the assumptions that are made in these five categories. It is therefore unavoidable that the lists of these assumptions will be long. Once these lists are initially completed, then they need to be checked against one another to ensure that they do not conflict If one set of assumptions is used to rationalize one suite of actions, and a conflicting set of alternative assumptions used for another suite, the program is internally inconsistent and obviously cannot succeed.

In regards to the second category of assumptions, *attributes* to *performance*, ***the scoring*** procedures used in doing the Patient-Template Analysis can be used to consider how productivity, key habitat, and attribute ratings would change under specific actions. Performance profiles can be then be re-examined under the new set of environmental scores to determine the extent of change to performance. Ultimately, one is really considering how extensively these scores need to be changed to effect the desired change in performance. Moreover, what assumptions must necessarily be made to realize these levels of change? Then., one can consider how reasonable these assumptions are.

Classification of Uncertainties

The next step in the benefit-risk analysis is to gain an understanding of the uncertainties of the stated assumptions and the implications of false assumptions. The following classification of uncertainties is useful in that it provides some organization to what might otherwise appear as a tangled web. It is based on three qualities or attributes of uncertainty: degree of uncertainty, consequences of error, and resolvability.

An uncertainty is classified as ACCEPTED when either the probability or the consequences of error are insignificant (Fig. 4.15). All others are labeled CRITICAL CRITICAL uncertainties in turn may be RESOLVABLE or UNRESOLVABLE.

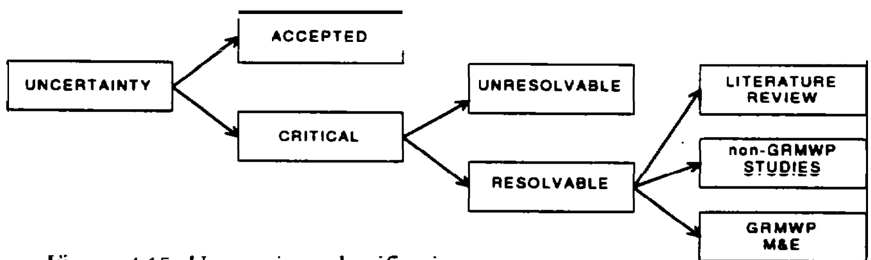


Figure 4.15. Uncertainty classification.

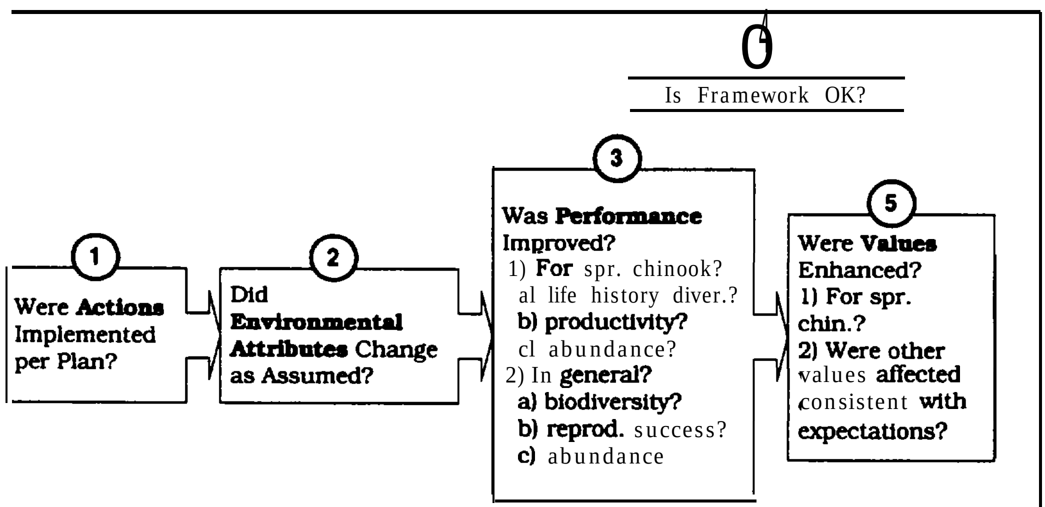
Resolution of uncertainties may be through literature review, studies outside the scope of the project, or studies that are a part of the project The monitoring and evaluation section which follows presents different ways in which uncertainties may be addressed within the project

Risk Analysis

The risk analysis is reported by value category and by objective. Using the list of assumptions and the associated uncertainty classifications, conclusions are stated regarding the risks to each management objective relevant to the project This step is likely best accomplished using a workshop format The list of assumptions and their uncertainty classifications is distributed to a group of individuals knowledgeable about a set of subjects that cover the range of values/objectives of concern to the watershed. The individuals are then asked to review the list from the perspective of their field of expertise. Three questions are then addressed in the workshop: 1) What are the risks [to objectives related to each individual's expertise] associated with uncertainty?, 2) Are there alternative actions available to achieve the same objectives? and 3) To what extent is it feasible to contain or resolve risks through monitoring? The purpose is to discuss and record conclusions to these questions. The purpose of the workshop is not to seek agreement on risk, but rather to capture a range of viewpoints in a clear and consistent manner.

Monitoring Approach Methods

Monitoring and evaluation (M&E) need to be an integral part of adaptive watershed management The purpose of M&E is to guide decision making toward implemenmtion of measures and actions that effectively contribute to achieving objectives while controlling risk It is a cornerstone of adaptive management, which is the imperative safety net of watershed stewardship in the face of uncertainty. Five levels of M&E[4] are described corresponding to five questions shown in Fig. 4.16. The questions correspond to the sequence of relationships embedded in the conceptual framework (see Fig. 4.3).



Fiie 4.16. Monitoring levels.

Level 1 M&E addresses the question of quality control. Its purpose is to determine if indeed the action was implemented as designed; i.e., was the work done in the right place, using the specified materials and methods? Quality assurance can and should accompany all implemented actions. This is important to assure effectiveness of the action and also to validate conclusions based on the assumption that it was indeed implemented as designed. Without quality control we have little confidence in any inferences drawn fiom our monitoring results. Most important in quality assurance is that the people performing the actions understand its intent and purpose. Quality

[4] /A similar approach was developed by the authors for the Yakima Fisheries Project.

control standards and procedures should be specified in the action plans and in contracts to perform the work

The second level of M&E asks whether the actions were effective in altering the environmental attributes. As Fig. 4.16 illustrates, actions are taken with the intent to modify (improve) a specified set of environmental attributes at given times and locations. These modifications in turn are expected to improve the performance of the biological system, which furthers progress toward the goal of enhancing values (e.g. greater abundance of the diagnostic species). Environmental attributes are notoriously variable; and therefore, monitoring plans must be statistically well designed to account for variation due to causes other than the action being taken.

Biological performance is generally difficult to observe directly. Level 3 M&E typically would consist of experimental testing of hypotheses regarding the response of populations to environmental factors. The rationale for a certain action may include assumptions about, for example, both current and future life history patterns of the diagnostic population. This suggests a hypothesis that members of the population are present in certain places at specific times, which can often be tested through observation. Hypotheses stated or implicit in the framework that form the rationale for the contemplated action should all be examined from the point of view of: a) what would the consequences of the action be if the assumption is false? b) how uncertain is the assumption? and c) can the assumption be resolved through a feasible experiment! This examination is a part of the benefit-risk analysis step in the planning process. The benefit-risk analysis, along with an assessment of the monitoring feasibility and cost, should form the basis for prioritizing the research that would be undertaken. It should be noted also that some of the critical hypotheses may allow broad inferences, with the implication that the research may have more global value and/or that it might be more appropriately conducted elsewhere.

Fundamental to the evaluation of watershed actions is the validity of the conceptual framework which forms the basis for interpreting all our observations. Both general and specific aspects of this framework should be subject to review and testing. Level 4 M&E is intended to capture the need to continually and progressively improve the theories that guide our decision making. Time and effort should be set aside for review of current literature on related subjects, thinking and creative exploration of new ideas, discussion and exchange of ideas, and active pursuit of critique and ideas from a broad range of interests and expertise. This level of monitoring may involve no direct fieldwork. It is important to keep in mind that monitoring at level 4 should also address the assumptions or conceptual framework regarding impacts on stakeholder values other than those that primarily motivated the contemplated action.

Level 5 M&E includes, for example, monitoring of the condition of the diagnostic species itself (e.g., run size, spawning escapement, etc.), which provides information essential to tracking the condition of the population over time. While erratic and imprecise as short term indicators (less than 30 years), trends in stock status are invaluable for assessing long term prognoses for populations and their environment. Level 5 monitoring would also deal with observations of other affected objectives and stakeholder values. The maintenance of a sense of history, in terms of conditions that reflect values and benefits to the community, is important as a long term guide for setting public policy and for detecting and responding to more gradual and insidious changes in the watershed. Level 5 monitoring provides a record for this broader, bird's eye view.

As stated above, monitoring and evaluation needs are determined by three factors: implication of error, uncertainty, and feasibility. The benefit-risk analysis examines the assumptions used in rationalizing actions. It identifies assumptions which, if erroneous, will render the action ineffective or even harmful; and it judges the degree of uncertainty about such assumptions. M&E plan development needs to be closely tied to the benefit-risk analysis. M&E is an important means for managing risk, and the ability to monitor may be a critical condition for proceeding with promising but uncertain actions.

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APPENDIX A

Forms Used in Assessment Procedures for Patient-Template Analysis

Appendix Table A- 1. Form used to assemble steam reach information for **Patient-** Template Analysis for spring chinook in the Grande Ronde Basin.

PATIENT

Reach name:											
Reach Location:											
Upstream reach 1:				Downstream reach 1:							
Upstream reach 2:				Downstream reach 2:							
Reach length:				Gradient (%): (SCHIN section)							
Estimated stream width during average year											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Source:											
Comment:											

TEMPLATE

Reach name:											
Reach Location:											
Upstream reach 1:				Downstream reach I :							
Upstream reach 2:				Downstream reach 2:							
Reach length:				Gradient (%): (SCHIN section)							
Estimated stream width during average year											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Source:											
Comment:											

Appendix Table A-2. Form used to assemble survival and environmental attribute information for Patient-Template Analysis for spring chinook in the Grande Ronde Basin.

Reach name:		Patient/Template:	
Utilization (Y or N):		Miles utilized:"	
Life stage:			
Wks of usage - Begin:		Wks of usage - End:	
Relative quantity of key habitat per unit area:			

Relative survival associated with habitat quality by month:											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Attribute	Rating	Source:	Comment:
Channel stability			
Flow			
Habitat type diversity			
Sediment load			
Water temperature			
Riparian condition			
Predators			
Chemicals			
Competitors			
Obstructions			
Water withdrawals			
Nutrient load			
Oxygen			
Pathogens			
Other			

General Comment

1/ Maximum miles for any life stage.

APPENDIX B

Summaries of Environmental Factors Affecting the Performance of Coho Salmon by Freshwater Life Stages and Associated Actions for Improvement

Table 1. Summary of environmental factors affecting freshwater population productivity and related density-independent survival by life stage of coho salmon. Potential mechanisms of mortality are also shown. Taken from Lestelle et al. (1993b).

Life stage	Factors affecting population productivity	Potential mechanisms affecting survival
Egg to emergent fry	Substrate stability, amount of fine sediment in spawning gravels, spawning gravel permeability, water temperature, peak flows	High flow events cause loss of eggs due to streambed scour and shifting (Tagart 1984); reduced flow and DO levels to eggs due to high sedimentation cause increased mortality (Tagart 1984); high tine sediment levels cause entombment of fry (Phillips et al. 1975); increased temperatures advance emergence timing, thereby affecting survival in next life stage (Holtby 1988); anchor ice reduces water exchange in redd causing low DO levels and/or eggs to freeze (Bjornn and Reiser 1991).
Emergent fry to September parr	Flow dynamics during emergence period, stream gradient, number of sites suitable for fry colonization, predators, temperature", , .nutrient loading[1/]	Loss of emergent fry occurs due to being displaced downstream by high flows (Holtby 1988); advanced emergence timing causes fry to encounter higher flows (Holtby 1988); high gradient and lack of suitable colonization sites for emergent fry cause fry to move downstream increasing risk of predation (Au 1972; Bjomn and Reiser 1991); stranding and death due to dewatering (Bottom et al. 1985); loss to predators (McFadden 1969); excessive temperatures promote disease and cause mortality (Bjornn and Reiser 199 I); temperature and nutrient changes affect growth thereby affecting other causes of density-independent loss (Bjornn and Reiser 1991; Hicks et al. 1991).
September parr to smolt	Fall and winter flows, number of accessible winter refuge sites, temperature, predators	Displacement during high flows (Scarlett and Cederholm 1984); stranding and death due to dewatering (Bottom et al. 1985; Cederholm et al. 1988); loss to predators (Zarnowitz and Raedeke 1984); loss due to poor health associated with winter conditions (Hartman and Scrivener 1990).[1/]

[1/] Effects likely have both density-independent and dependent components.

Table 2. Summary of possible habitat enhancement measures to increase freshwater density-independent survival of coho salmon by life stage. Taken from Lestelle et al. (1993b).

Life stage	Habitat enhancement measures	Effects on productivity and survival
Egg to emergent fry	Spawning beds stabilized using smooth sloped berms and deflectors (Bauer *personal communications)* and other in-stream structures (Overton 1984). opening of relief channels (Bottom et al. 1985). developing stable side channels for spawning (Bachen 1984). and reducing sediment inputs (Lisle 1981); sediment inputs reduced by restoring riparian vegetation (Lisle 198 I; Bottom et al. 1985) and controlling road runoff (Reeves et al. 1991); gravels cleaned by mechanical cleaning techniques or clean gravels added (Reeves et al. 1991); peak flows ameliorated by opening relief channels and creating wetlands and ponds (Gordon et al. 1992).	Density-independent component of egg to emergent fry survival increased by improving overall quality of egg incubation environment.
Emergent fry to September parr	High flows during spring runoff ameliorated as described above; colonization sites for newly emerged fry added by constructing backwater pools and alcoves (Reeves et al. 1989; Nickelson et al. 1993) or adding brush piles to mainstem channels (Peters et al. 1992); temperatures ameliorated or augmented through selective cutting of streamside vegetation (Murphy and Meehan 199 I); nutrient loads enhanced through fertilization (Perrin et al. 1987) or managed riparian vegetation (Murphy and Meehan 1991).	Density-independent component of emergent fry to September parr survival improved by increasing the probability of newly emerged fry finding suitable colonization habitat, reducing severity of summer high temperatures, or improving growth through increased metabolism.
September parr to smolt	High flows during fall and winter ameliorated as described above; overwintering sites for parr added by constructing backwater pools and alcoves (Nickelson et al. 1992b and 1993) and off-channel ponds (Cederholm et al. 1988).	Density-independent component of September parr to spring smolt survival improved by increasing the probability of parr finding suitable overwintering habitat, or reducing effects of major floods on habitat.

Table 3. Summary of environmental factors affecting freshwater habitat capacity and related density-dependent survival by life stage of coho salmon. Potential mechanisms of mortality are also shown. Taken from Lestelle et al. (1993b).

Life stage	Factors affecting habitat capacity	Potential mechanisms affecting survival
Egg to emergent fry	Total quantity of suitable and accessible spawning sites (incorporates channel gradient, flow patterns, water depth, and substrate size)	Competition for spawning sites causes eggs to be deposited in unfavorable areas increasing mortality (McFadden 1969); redd superimposition causes displacement of eggs (McNeil 1969); high egg densities increase biochemical oxygen demand and metabolic wastes and increases mortality (Hunter 1959); low DOs decrease fry size (Shumway et al. 1964) affecting density-dependent interactions in subsequent life stage.
Emergent fry to September parr	Total quantity of accessible summer rearing habitat by habitat type (incorporates pool-riffle composition, stream gradient, pool types. summer low flows); temperature"; nutrient loading; sunlight exposure; predators"	Competition for required habitat following emergence causes displacement of fish downstream and increases mortality (Chapman 1962; Au 1972); temperature, nutrient loading and exposure to sunlight affects food production, which affects rearing capacity. fish size. and associated density-dependent survivals during summer and winter (Murphy and Meehan 1991; Hartman et al. 1987; Holtby 1988); density-dependent growth affects loss rate to predators (Allen 1969).
September parr to smolt	Total quantity of accessible winter habitat by habitat type (incorporates all in-channel and off-channel overwintering type habitat; amount of woody debris may influence habitat capacity)	Size of fish entering winter (resulting from density effects in previous stage) affects overwintering survival (Holtby et al. 1989); density of juveniles entering winter stage directly or indirectly affects overwintering survival (evident in data of Au 1972 and Holtby et al. 1989). though evidence of direct competition for winter habitat is lacking - observations by Onodera (1962) suggest such competition can occur.

" Effects likely have both density-independent and dependent components.

Table 4. Summary of possible habitat enhancement measures to increase habitat capacity and associated density-dependent survival of coho salmon by life stage. Taken from Lestelle et al. (1993b).

Life stage	Habitat enhancement measures	Effects on habitat capacity and survival
Egg to emergent fry	Amount of spawning habitat increased by installing structures to catch and retain gravel or by addition of new gravel (Reeves et al 1991), reopening and rehabilitating old stream channels for spawning (Gordon et al. 1992), and opening new areas blocked to anadromous migration (Reeves et al. 199 l).	Density-dependent component of egg to emergent fry survival improved by increasing amount of spawning area, thereby reducing competition for existing spawning sites.
Emergent fry to September parr	Create new fry colonization sites by adding backwater pools and alcoves (Reeves et al. 1989; Nickelson et al. 1992b) or adding brush piles to mainstem channels (Peters et al. 1992); increase pool-riffle ratio by creating new pools (Reeves et al. 199 l ; Gordon et al. 1992); increase productive rearing capacity of habitat by nutrient enhancement (Perrin et al. 1987) and/or improvement of temperature regimes (Murphy and Meehan 1991); open new areas blocked to anadromous migration.	Density-dependent component of emergent fry to September parr survival improved by increasing the amount of rearing space and/or food production, thereby reducing competition for existing resources.
September parr to smolt	Create new overwintering habitat by constructing backwater pools and alcoves (Nickelson et al. 1992b and 1993) and off-channel ponds (Cederholm et al. 1988) and increase capacity of habitat by adding woody debris (Nickelson et al. 1992b); provide access to off-channel habitat (ponds and lakes) currently blocked (note: these areas may actually be contained by the existing stream channel but may be screened to prevent emigration of stocked trout as occurs on many natural lakes in western Washington).	Density-dependent component of September parr to spring smolt survival improved by increasing the amount of overwintering space, thereby reducing competition for existing resources.